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Science & Technology

Japan

SPACE ARTIFICIAL INTELLIGENCE/ROBOTICS/
AUTOMATION SYMPOSIUM

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SCIENCE & TECHNOLOGY

JAPAN

SPACE ARTIFICIAL INTELLIGENCE/ROBOTICS/ AUTOMATION SYMPOSIUM

43062507 Tokyo PROCEEDINGS OF THE 2ND SAIRAS in Japanese 17-18 Nov 88 pp 1-173

[Selected papers presented at the Second Space Artificial Intelligence/ Robotics/Automation Symposium held 17-18 Nov 88 in Tokyo]

CONTENTS

New Technology Development for Space Infrastructure

43062507a Tokyo PROCEEDINGS OF THE 2ND SAIRAS in Japanese 17-18 Nov 88 pp K14-19

[Article by Masami Ikeuchi, Tsukuba Space center, National Space Development Agency of Japan]

[Excerpt] [Passage omitted] **2. Elements Comprising Space Infrastructure and Fundamental Technologies Supporting the Elements**

The space infrastructure is basically made up of the following:

- Permanent facilities in space: Permanent manned space station; platforms; orbital work modules.

- Transport means: Rockets; space shuttle; inter-orbital transport vehicle.

- Support systems: Data communications systems for communications between satellites; support systems at the launch and recovery sites of space vehicles.

Shown in Figure 1 are these space infrastructure elements classified by mission execution system and common support system. The space station is used for such mission-execution capabilities as materials, life sciences, science and engineering experiments, and scientific observations, as well as for support capabilities such as providing orbital services to the platform and other space systems. Because of its capabilities and its scale, the space station is the central component of the space infrastructure.

Figure 2 shows the fundamental technologies supporting the space infrastructure. In the fields of launch technology and the bus technology of conventional satellites, proprietary technologies have been accumulated during the development of the H-II rocket and the ETS-VI. However, R&D has just been started on the recovery technology for returning space achievements from orbit and, in connection with this technology, on orbital services, technology, such as equipment maintenance, inspection, repair, exchange and supply, as well as on the data relay and tracking technology needed for the high-level operations of various types of spacecraft. The emphasis of the National Space Development Agency's activity is placed on the R&D of these technologies.

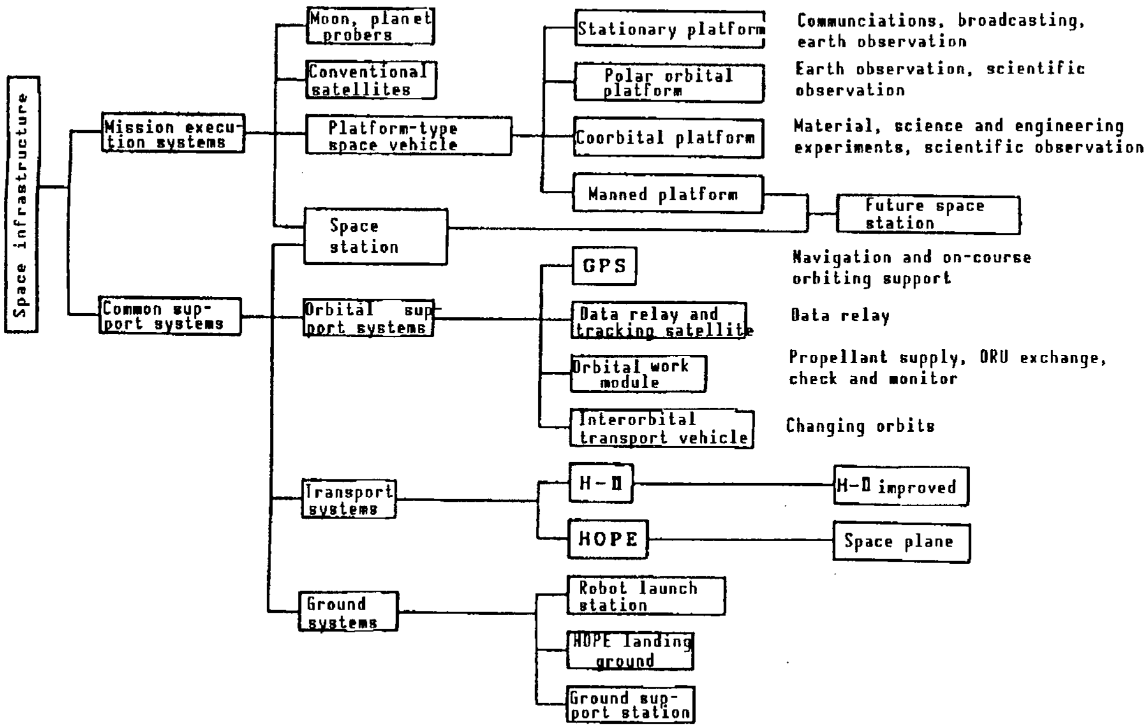

Figure 1. Elements Comprising Space Infrastructure

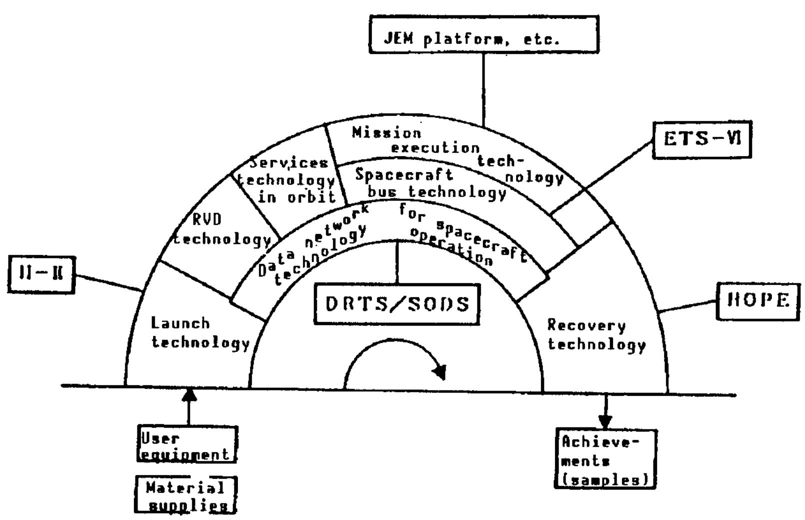

Figure 2. Fundamental Technologies Supporting Space Infrastructure

3. Progress of R&D on Major Components of Space Infrastructure

Figure 3, conceptual diagrams of major systems representing the component elements of the space infrastructure, which the National Space Development Agency has either developed or for which it is currently in the research and development stage, are shown. Systems shown on the right of the broken line are the R&D targets. The space station is shifting to the development stage, and has been introduced in various publications. Therefore, in the following major systems other than the space station are described.

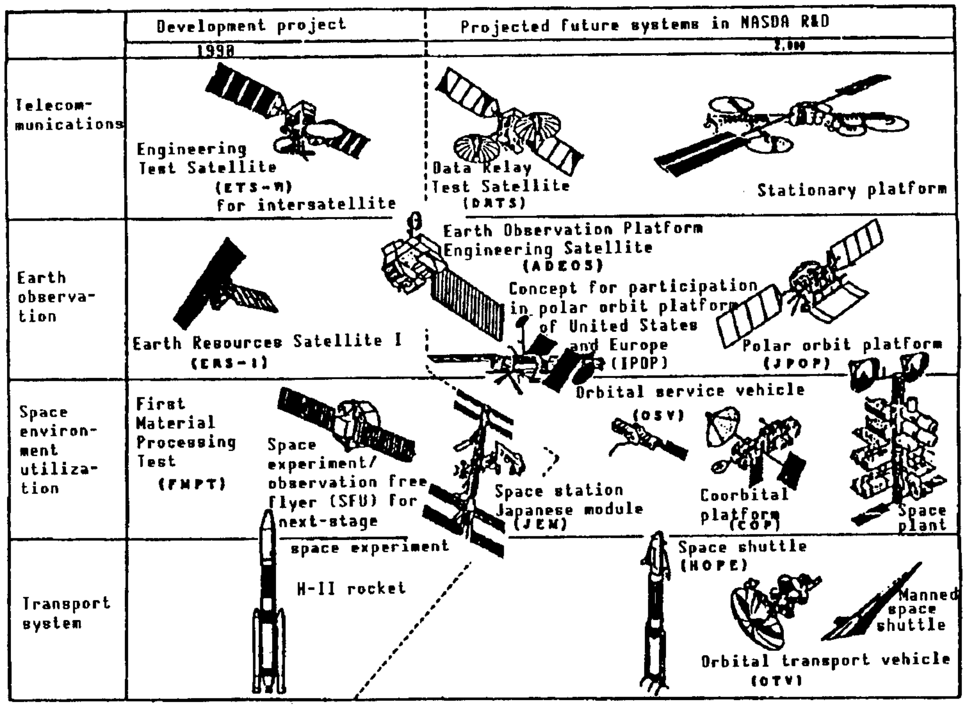

Figure 3. Outlines of Long-Term Perspective

3.1 Space Environment Utilization System

Of the major systems comprising the space infrastructure, the platform-type space vehicle is as important as the space station. Differing from the conventional type of satellite, the platform-type space vehicle is not a disposable type of system and, while in orbit, it can receive supplies of fuel, and malfunctioning systems or instruments on board the vehicle can be repaired or replaced. In other words, if provided with orbital services,the platform-type space vehicle is capable of sustaining a long life and is also capable of performing multipurpose missions--a so-called "Large-Scale Satellite System."

As for the structure of the platform-type space vehicle, although co-orbital, planar orbital and stationary orbital platforms exist, we have taken on the conceptual design of a co-orbital Application Technology Platform (ATP) aimed at establishing the technological foundations necessary for a platform-type space vehicle and the technologies necessary for unmanned experiments in space, as well as providing the means for the space environment utilization needs. The results have led to a concept consisting of three modules--mission, resources and propulsion. We are also engaged in researching the major elemental technologies of the platform-type space vehicle, such as rendezvous/docking technology including the partial trial manufacture of rendezvous radar, two-phase fluid loop-type heat dissipation technology for controlling large amounts of heat and flexible solar cell paddle technology for generating large electric output.

In Figure 4 is the conceptual diagram of the Application Technology Platform. As stated above, the platform-type space vehicle is designed to receive services in orbit by rendezvousing or docking with the space station. We are also studying an engineering test space vehicle that will be used to demonstrate the platform-type space vehicle's capabilities to rendezvous and dock with the space station and receive services from it in orbit.

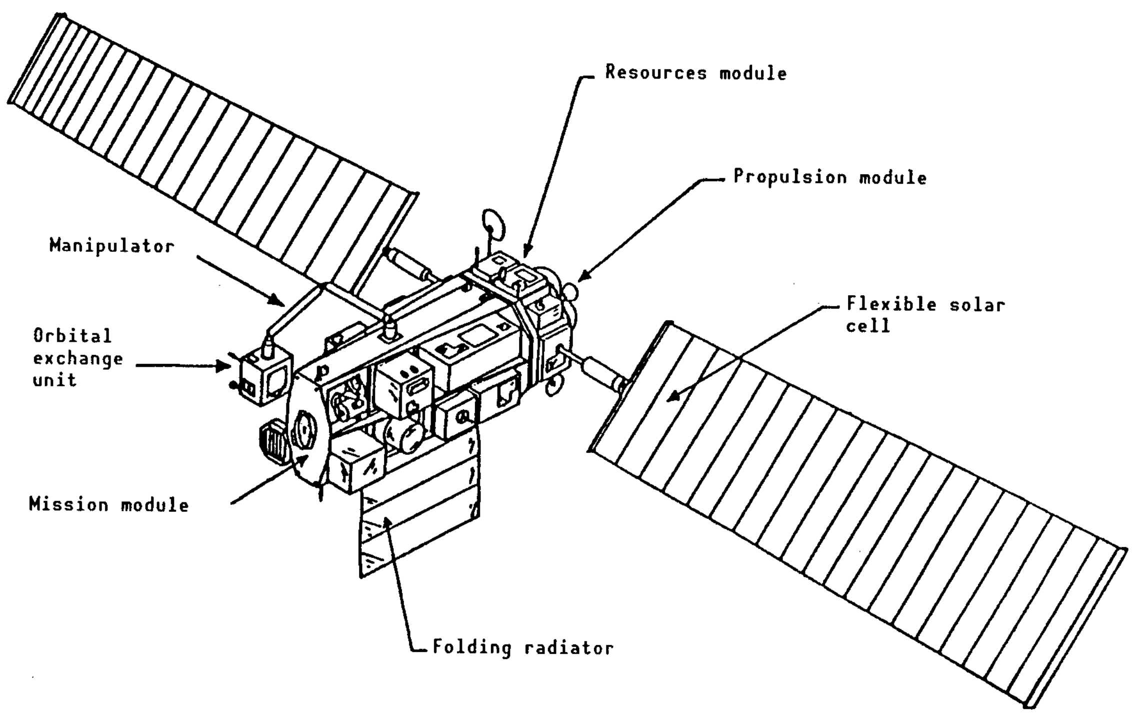

Figure 4. Conceptual Diagram of Application Technology Platform

3.2 Space Transportation System

Research is being conducted involving the systems concepts of the space shuttle HOPE that will be launched using an H-II rocket. HOPE is designed for use in such missions as providing supplies to and recovery of materials from platform-type space vehicles, and recovering research achievements from space stations/JEM in the mid-1990s and thereafter. As for HOPE, studies have been made of a shuttle weighing about 10 tons, which is the upper limit of the H-II rocket's capacity to launch a payload into low orbit, and on a 7-ton-class shuttle that will be able to recover minimum payloads from JEM according to the design. Studies have also been made on the specifications demanded of the subsystems, as well as on the concept and development plans of an experimental vehicle. As for HOPE, research is being advanced jointly with NAL of technical tasks in such fields of aerodynamics as wind tunnel testing, heat structures, and guidance and control. As for elemental technologies, basic tests have been conducted on the main structural materials and thermal insulating materials that will be used in HOPE's frame, and testpiece-level data on thermal and mechanical characteristics are being obtained. Research is being conducted involving guidance and control technology, representing important technology for HOPE which is scheduled to be equipped with unmanned operation and automatic take-off and landing capabilities.

Figure 5 gives a conceptual diagram of HOPE as a result of studies conducted to this point.

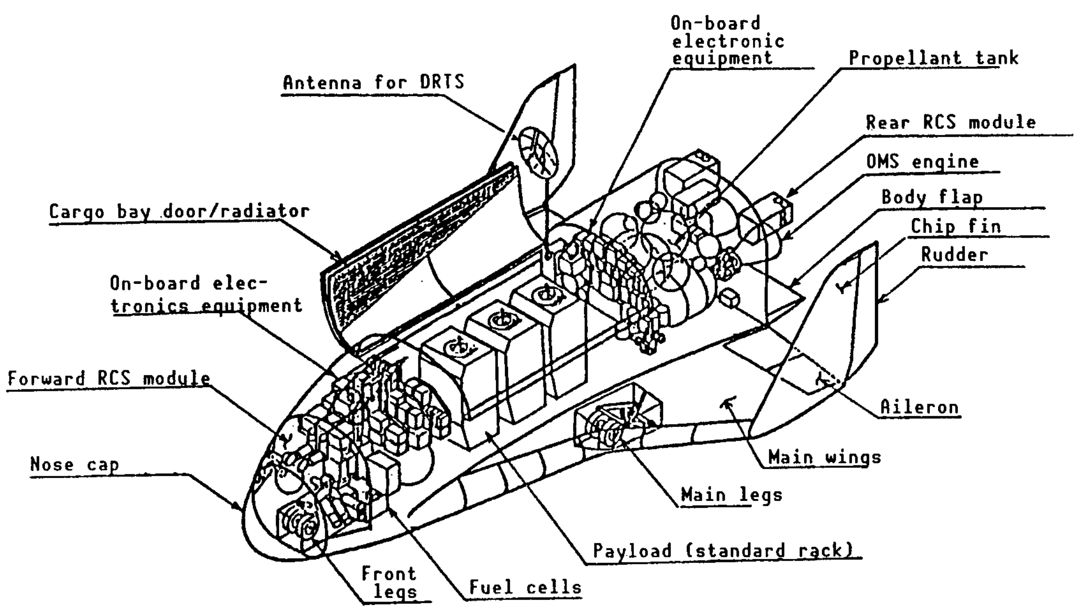

Figure 5. Conceptual Diagram of HOPE

3.3 Earth Observation System

As an extension of the MOS-1 and ERS-1 launched last year as well as in response to the earth observation needs of Japan and the world and, furthermore, to maintain and develop Japan's earth observation technology, work is being undertaken to draw a conceptual design of the earth observation platform technology space satellite (Advanced Earth Observation Satellite (ADEOS)). In keeping pace with the work on the conceptual design of ADEOS, research has been made of an earth observation data receiving and processing system for the future mainly by the Earth Observation Center, and a list of required on-board and ground systems has been prepared. As for the ocean color and temperature scanning radiometer (OCTS) to be installed aboard the ADEOS, major constituent elements of the system, such as the scanning mechanism, radiator, detector and light-gathering optics, have been partially manufactured on a trial basis, and research of the system design is underway. As for the high-performance (advanced) visible near infrared radiometer (AVNIR) also scheduled to be carried aboard the ADEOS, research involving the system design has been conducted and the concept of the on-board system has been obtained. Drawing on these achievements, the ADEOS entered the developmental research phase in FY 1988.

Research is currently being conducted involving the system design of an advanced microwave radiometer (AMSR) capable of observing multiple frequencies by means of electronic scanning and which is scheduled to be mounted on the polar orbital platform planned by the United States and Europe (IPOP) illustrated in Figure 6 [not reproduced], and critical components have been manufactured on a trial basis to obtain the basic data.

3.4 Data Relay and Tracking Satellite System

The conceptual design of the data relay and tracking satellite (DRTS) system designed to open the way for the high-level operations of various types of space vehicles around the year 2000 and thereafter has been obtained. Studies and surveys have been conducted on such items as the demand for the DRTS data transmission service that the user space vehicle will have, frequencies to be used for data communications, and interoperations of NASDA/NASA/ESA data relay satellite systems, and mission requirements in the conceptual design phase have been established. After considering the preconditions demanded for the development of DRTS, such as mission requirements and the effective use of an ETS-VI bus, an analysis has been made to determine what missions DRTS will be called upon to conduct, and its schematic systems configuration has been elucidated to satisfy the mission requirements. Work is now underway to sort out major systems requiring development. As for the DRTS' major developmental item, a 5-meter-class folding antenna for communications between satellites work has been started on the trial manufacture of a test model to confirm the systems capability to unfold. Research is also in progress on methods of attitude control when the antenna is moving.

Work has been started on the design of experimental models of a 20-w-class TWTA in the 32 GHz range for use as an intersatellite communications system by user space vehicles and of a wide-angle gimbal.

As for the intersatellite communications experiment to be carried out using the ETS-VI before the DRTS goes into operation, ADEOS has been selected as the other party in the satellite-to-satellite communications experiment and plans for the experiment have been drawn up. The experimental systems and equipment to be carried aboard the ETS-VI are being trial manufactured.

Among the systems under consideration for possible installation aboard the experimental data relay and tracking satellite (EDRTS) that is scheduled for launching before the DRTS is lifted are high-performance mobile satellite communications experimental equipment and 12 GHz broadcasting experimental equipment, in addition to k-band and s-band intersatellite communications equipment. Figure 7 is a conceptual drawing of the EDRTS with these mission systems and equipment on board.

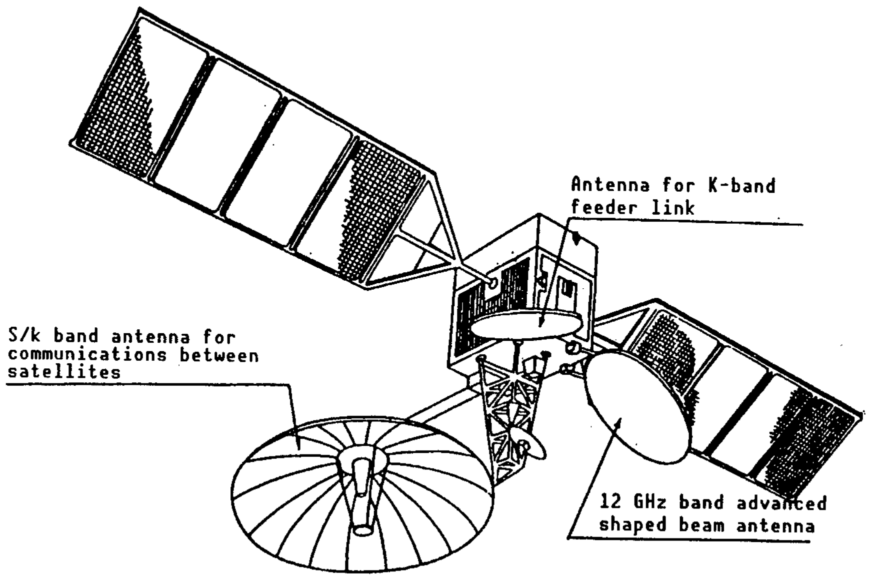

Figure 7. Conceptual Drawing of EDRTS

3.5 Common Technologies and Development of Components

The author has introduced NASDA efforts for the R&D of major systems making up the space infrastructure, but we at NASDA are also advancing R&D at the levels of the subsystems making up those major systems, components and parts. In addition to promoting the development of parts for the H-II rocket and ETS-VI, we are also conducting research into such common technologies as the radiation degradation of semiconductor devices, basic experiments relating to a "single event,' and the research and assessment of the properties of space materials involving withstanding oxygen atoms. THe trial manufacture and evaluation of the components of a high-performance Ni-Cd battery and an Ni-Hz batter are also being undertaken.

Among other common technologies being researched are the assessment and analysis of artificial satellite operations data; the testing of a tune dry gyro (TDG) to assess its reliability; measuring the life of a momentum wheel; the trial manufacture and evaluation of a high-precision earth sensor, high-precision solar sensor and small reaction wheel; a study of the installation technology of electronic systems; a study of a high-precision three-axis attitude control system; the study of the future space vehicle; the study of a space environment model; the study of a thermal power-generating system; the study of laser communications between satellites; the study of an optical data bus for space; the study of high pulse compression technology for active earth observation radiowave equipment; the study of propulsion technology;

and joint research with NHK involving the installation technology of a 200-w-class repeater. Furthermore, since FY 1985 research has been conducted on IRCCD, aiming at the development of an IRCCD radiometer for installation on-board the next-generation geostationary weather satellite, and research on the crystallization process has been completed. Since FY 1988 research has been underway on the fabrication of devices. The partial trial manufacture of the critical elements of the space cooling system needed to maintain the IRCCD at extremely low temperatures in space has been undertaken. In FY 1987, space artificial intelligence/robot research was added as a common technology, and research is being conducted on the system's concrete elemental technology--partially autonomous/remote controlled space robot technology--in addition to the study systems configuration of the orbital space vehicle (OSV). [Passage omitted]

Payload Inertia Used in Control of Master-Slave Manipulators

43062507b Tokyo PROCEEDINGS OF THE 2ND SAIRAS in Japanese 17-18 Nov 88
pp 3-6

[Article by Tadashi Komatsu, Michihiro Uenohara and Shoichi Iikura, R&D Center, Toshiba Corp.]

[Excerpts] [Passage omitted] 2. **Master-Slave Manipulators for Use in Space**

There is basically no difference between the system configurations of ground and space master-slave manipulators, i.e., an operator in a safe environment manipulates the master arm, while the slave arm, in a special environment, executes the work in response to the commands received. The master-slave manipulator for use in space, however, is thought to involve the following items, in addition to its space specifications.

(1) The slave arm executes work in a nongravity environment.

(2) There is a limit to the space inside the operation chamber.

(3) The distance between the master and slave is sometimes very greater (such as between the ground and space).

Of the above, item (1) is dealt with in this paper. In contrast to a slave arm used on the ground, that used in a nongravity (microgravity) environment is sometimes required to handle objects of large mass. In such a case, it is difficult to distinguish the inertial force of the payload from the external force working on the payload, which affects the operability of the arm.

Item (2) is related to the master arm configuration. If the limited space inside the pressure chamber is to be fully utilized, the systems and equipment installed will have to be very compact. The master arm is not an exception to the rule, but must be very compact and characterized by ease of operation. On the ground, master arms of the same structure and scale are widely used, but for use in space, we believe that devices of different structures, such as a hand controller, are highly effective. At Toshiba Corp.'s R&D Center, we have manufactured this type of master arm on a trial basis, and its details are given in Reference 1.

In item (3), time delays affect the control system, and this problem is mainly associated with teleoperator systems.

3. Inertial Force Compensations in Bilateral Control

We regard the so-called bilateral control system, in which work is conducted according to force sensations, to be very effective in space operations. Since, in this control method, the operator executes his job while obtaining feedback of the external force working on the slave arm via the master arm, this technique enables high-precision operations, to be performed. However, in some operations, such as that in which a payload with a large mass needs to be handled and latched onto a coupling mechanism, the coupling power may be hidden behind the payload's inertial force, making it impossible for the operator to fully grasp the situation.

With the objective of compensating for the payload's inertial force, we propose the control system shown in Figure 1. It is based on a force feedback-type of bilateral control.

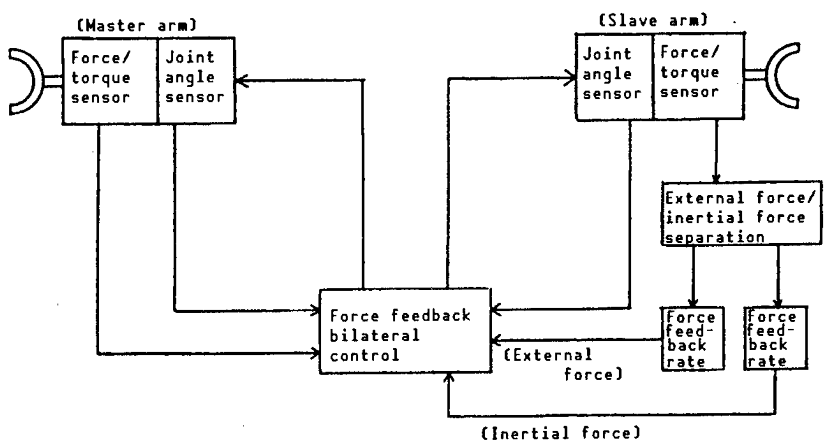

Figure 1. Block Diagram of Control

In order to compensate for inertial force, the value of the inertial force must be determined accurately. To that end, two methods are studied: one is to attach an acceleration sensor to the center of gravity of the payload, while the other is to obtain the value through calculations from the payload's orbit of motion. One problem with the former method involves wiring for sensor signals, while the latter method does not seem to be applicable to a master-slave system since it is very difficult to predict the orbit.

Therefore, in the system we have proposed, the sensor signal is first estimated using a Karman's filter and then an estimate is made of the inertial force. In obtaining the mathematic models for the force sensing process, we used the model developed by Uchiyama, et al., to isolate gravity from inertial force. According to the model, the following equation of state is generated

$$\dot{x} = Ax + Bv \tag{1}$$

where

$$x = [X,\ \dot{X},\ Fs,\ Fo]^t \tag{2}$$

$$v = [v_s,\ v_o]^t \tag{3}$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & -m^{-1} & -m^{-1} \\ 0 & 0 & -\omega_s & 0 \\ 0 & 0 & 0 & -\omega_a \end{bmatrix} \tag{4}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \omega_s & 0 \\ 0 & \omega_a \end{bmatrix} \tag{5}$$

as is the equation of observation

$$y = Cx + w \tag{6}$$

where

$$y = [X,\ -Fs]^t \tag{7}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \end{bmatrix} \tag{8}$$

Here, however, the motion is limited to one direction and X: the absolute coordinates of the payload's center of gravity; Fs: the force that the arm exerts on the payload; Fo: external force; v_s, v_o: Gaussian white processes; m: payload mass; ωs, ωa: cut-off frequencies to u_s, u_a; W: observation noise.

By breaking up formulae (1) and (6) and by solving discrete Riccati equations, the constant Karman's gain was obtained, which was used to estimate the external force Fo. Subtracting F_o from Fs enables the inertial force F_I to be obtained. After being multiplied by the appropriate feedback rates, Fo and F_I are used for bilateral control calculations.

4. Experimental Equipment

Figures 2 and 3 [not reproduced] show the experimental systems used in the tests of the control method in question.

Shown in Figure 2 [not reproduced] is the slave arm, which measures 1.6 meters in overall length and has three degrees of freedom in its shoulder, elbow and wrist. Floating over a fixed board by means of an air bearing, the arm is placed in a simulated nongravity environment. Shown in Figure 3 [not reproduced] is the master arm. Although not a hand controller, it is a sort of minimaster, measuring 0.6 meter in overall length and is compact. Both are driven by a DC motor. As for sensors, potentiometers are used for joint angles, but for force/torque sensors, the slave has a three-axis-type, while the master is provided with a single-axis torque sensor. Motorola's VME-10 is used as the computer.

5. Experimental Results

To investigate the state of separation between the external force and inertial force, we first conducted the following two experiments. In the first experiment, the slave arm was made to carry a 40-kg payload and to take an L-shaped posture, bent about 45 degrees at the elbow. The arm was moved transversely to the base section by means of unilateral maneuvering via the master arm and, using a spring balance, an external force was applied to the payload halfway through the process. Results of the experiment are shown in Figure 4. From the top, the diagrams show the absolute coordinates of the slave arm's tip, the output values of the three-axis force/torque sensor, estimated values of the external force, and estimated values of the inertial force, respectively.

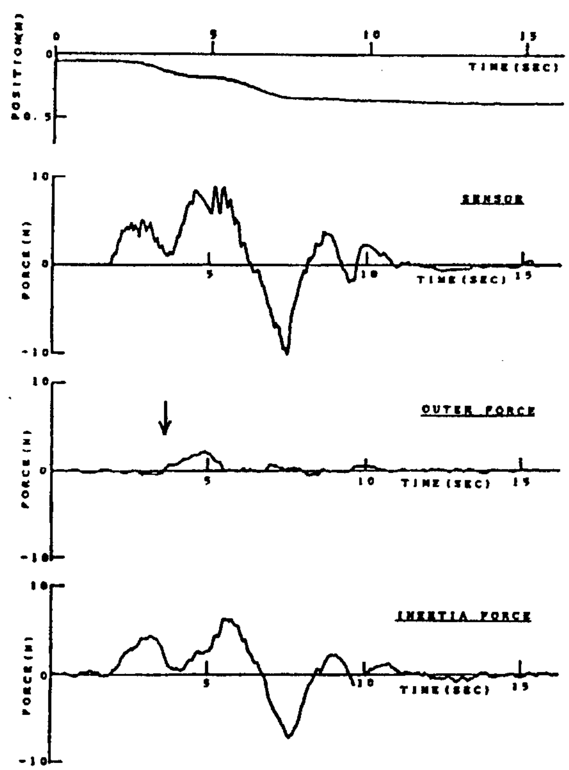

Figure 4. Experimental Results (External disturbances applied via a spring balance)

Approximately 2 seconds after the arm started moving, an external force was applied. Although not apparent from the sensor output values alone, the estimated values of the external force clearly reveal the force elements being applied to the payload.

The second experiment was conducted under the same conditions as the first experiment, and a portion of the payload was made to collide with a block. Figure 5 shows the results. Analysis of the sensor values reveals two large peaks in the positive direction. Of them, the peak appearing around 7 seconds contains the force of impact generated when the payload struck the block.

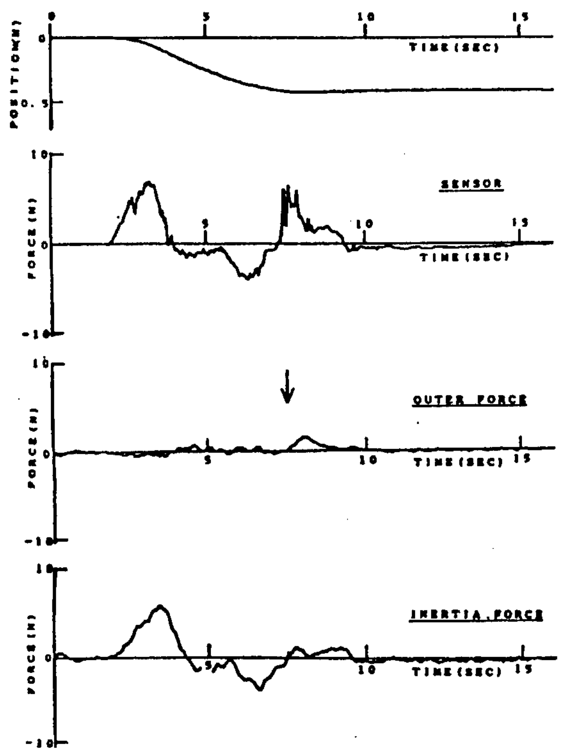

Figure 5. Experimental Results (Collision with a block)

From the foregoing experiments, it has been confirmed that the external force can definitely be separated from the inertial force.

Next, we experimented with bilateral control using the above technique. As with the previous experiments, in the current experiment we set up the slave arm to handle a 40-kg payload and the operator manipulated the master arm through bilateral control. The work here involved attaching pins to two positions at the tip of the payload and inserting those portions into two holes drilled into a block. The clearance at this time was 100 μm. We used the control method shown in Figure 1, i.e., the inertial force of the payload and the outer force working on the payload, separated by means of Karman's filter, were multiplied by the appropriate feedback rates, and these values were used for bilateral control. The values we used this time were 0.2 for the inertial force and 2 for the external force.

The results of the experiment are shown in Figure 6. From the top, the angles of the joints at the shoulder and elbow of the master and slave, the output values of the torque sensors at the shoulder and elbow of the master

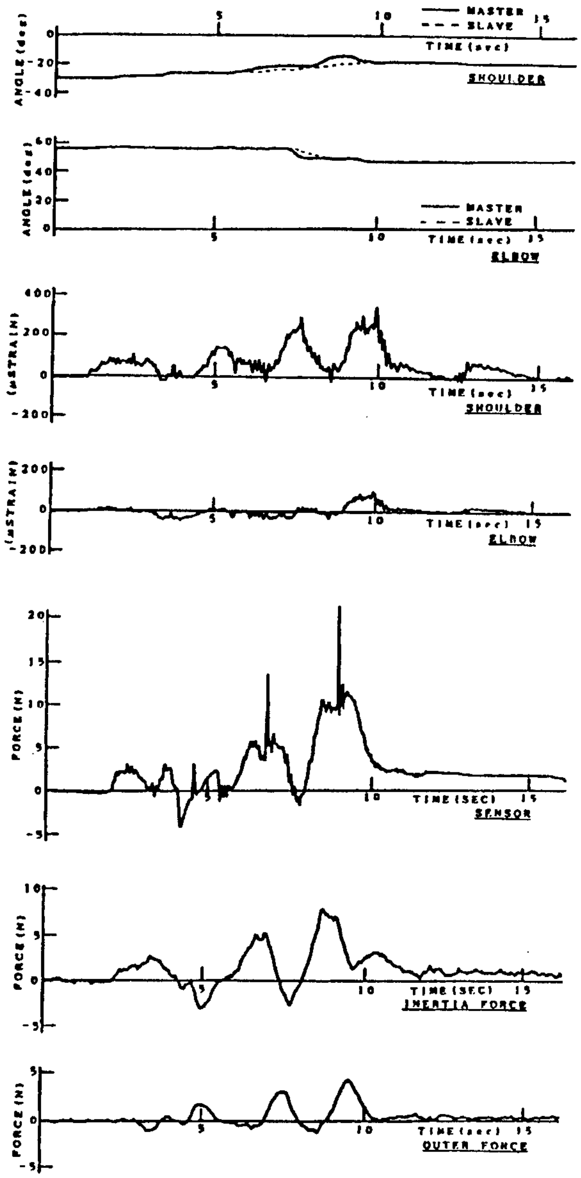

Figure 6. Experimental Results (Bilateral control)

arm, the output values of the three-axis force/torque sensor on the slave arm, and estimates of the inertial force and outer force are plotted. In this operation, the operator managed to obtain an insertion after letting the pins collide with the block surfaces near the holes approximately three times, so the results are manifested in the estimated values of the external force. The output values of the torque sensor on the shoulder of the master arm correspond to the force senses that the operator actually felt. As is demanded when setting the feedback rate, the external force is emphasized. With conventional methods, the inertial force becomes dominant. Conversely, when there is no inertial force, the master arm tends to be thrown about, so it is dangerous. Sampling was 16 meters per second.

5. Conclusion

We have proposed an inertial force compensating type of bilateral control using Karman's filter and have examined its practicality in an experiment.

References

1. Shinomiya, et al., "Development of Hand Controllers for Robots," Proceedings of the 32nd Combined Lecture Session on Space Science and Technology, 1988.

2. Uchiyama, et al., "Dynamic Sensing of Robot Fingers Six-Axis Force," JOURNAL OF THE JAPAN ROBOTICS SOCIETY, Vol 4 No 6, 1986, pp 3-11.

Prototype of Short Range Sensor for Proximity Operation in Space

43062507c Tokyo PROCEEDINGS OF THE 2ND SAIRAS in Japanese 17-18 Nov 88
pp 51-54

[Article by Kazuo Machida, Yoshitsugu Toda and Toshiaki Iwata, Electrotechnical Laboratory, and Michihiro Uenohara, Tadashi Komatsu, Shoichi Iikura and Masaru Oka, Toshiba Corp.]

[Text] **1. Foreword**

As activity in space accelerates in the future, the demand for robots, e.g., manipulators, will inevitably rise. The key to expanded space activity is robot automation, it boils down to eliminating as much as possible the human factor from their operation. Making a robot operate autonomously without the help of the operator will also lead to upgrading its capabilities and performance. If a robot is to be able to operate autonomously, the system must be equipped with a vision system capable of detecting the position of the object it is going to work on in real time. We have developed a sensor of a relatively simple structure, capable of detecting the three-dimensional position and attitude of an object, for use in proximity operation on board a space vehicle. When the object is provided with a target, this sensor is capable of high-speed image processing without the help of high-performance processors.

2. System Configuration

This sensor is comprised of a small CCD camera for detecting the target, a lighting system for illuminating the target and a controller that calculates the three-dimensional position and attitude of the object by processing the video signals outputs from the camera. The object for position and attitude detection is provided in advance with a five-mark target.

2.1 Target

Figure 1 shows the shape of the target. The target consists of five marks, including four marks arranged in the form of a rectangle on the target plane and one on the top of a pole. The pole is erected at the center of the four-point rectangle, perpendicular to the target's plane.

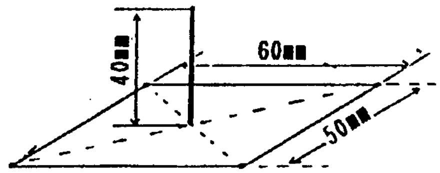

Figure 1. Target

2.2 Controller

Figure 2 shows a block diagram of the controller. Video signals from the CCD camera are processed in the hardware and a mark equivalent to a high luminescence point is detected. The horizontal and vertical positions on the screen of the detected mark are calculated, the former by counting the time from the horizontal synchronous signal and the latter by counting the number of scanning lines, as shown in Figure 3. Resolution is 250 for both the horizontal and vertical directions. These values are recorded in the buffer memory, permitting access from the CPU. Consequently, the number of software-based image data is extremely small, enabling the high-speed position and attitude to be detected.

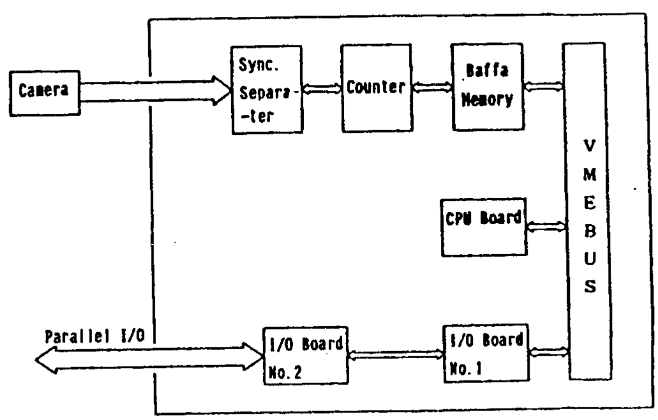

Figure 2. Controller

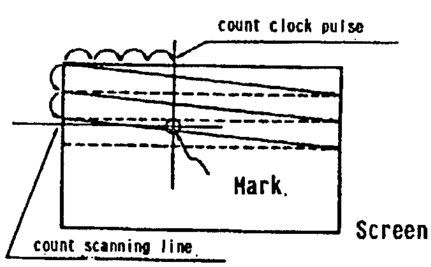

Figure 3. Position in the Screen

The CPU comprises a 32-bit 68020 microprocessor and a 68881 coprocessor for numerical computation. The CPU reads the data in the buffer memory, conducts image processing calculations and reverse transformation calculations on projections, and obtains the three-dimensional position and attitude of the target. If the amounts of movement between the coordinate systems are provided in advance by the host computer, it is possible to transform the position and attitude into those for any random coordinate system and to output the results.

Exchange of data with the host computer can be had by parallel interface via an I/O board.

3. Calculations of Three-Dimensional Position and Attitude

If a target is installed on the object, this sensor can calculate the three-dimensional position and attitude by using a single-eye camera. Generally, if the geometrical positional relationships are known through a set of four points on the same plane in a three-dimensional space and if positions corresponding to those points are obtained on an image, the three-dimensional positions of those four points can be uniformly determined from the reverse transformation of projection. Consequently, four marks are the minimum required; however, in our sensor, an additional point is provided in order to improve the accuracy of attitude.

Shown in Figure 4 is a state of perspective transformation from a camera coordinate system (Σ_c), i.e., three-dimensional orthogonal coordinates with the camera as the origin, into a frame coordinate system (Σ_f) within the image. Each mark is expressed by the following perspective transformation formulas

$$x_i^f = \frac{y_a}{Y_i^c} X_i^c \qquad (i = 1, \cdots 5) \tag{1}$$

$$y_i^f = \frac{y_a}{Y_i^c} Z_i^c \tag{2}$$

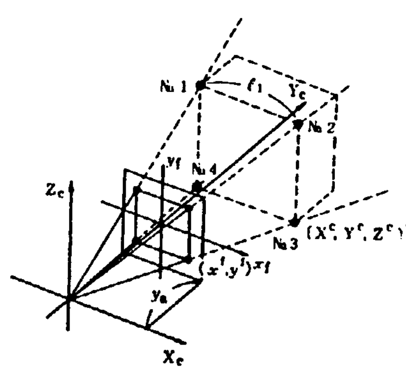

Figure 4. Perspective Transformation

By substituting formulas describing the relative positional relationships (distance, angle, etc.) of the mark for the above formulas and by eliminating unknown quantities, the three-dimensional position of the mark can be obtained. In this case, the diagonal lines of the rectangle intersecting at the center and the length of a side of the rectangle are used as the relative positional relationships. This is expressed by the following equations.

$$X_1^c + X_3^c = X_2^c + X_4^c \tag{3}$$

$$| X_1^c - X_2^c | = \ell_1 \tag{4}$$

where $X_i^c = [X_i^c, Y_i^c, Z_i^c]$, and the position vector on the camera coordinate system of the mark is in the i-th place.

Furthermore, the use of the length of the pole makes it possible to obtain the position of the mark at the pole's top.

When the three-dimensional positions of each of the marks have been obtained by the procedures described above, the attitude of the target plane can then be obtained by using those values. The attitude can be obtained only from the four points in the target plane, but when the target plane is facing the camera squarely, with little inclination, the pitch and yaw angles cannot be obtained as accurately as the roll angle.

When obtaining the tilt of the target plane from the positions of the four points comprising a rectangle, the distortion of the square made up of the four points in the image derived from the rectangle is reflected as the tilt of the target plane. However, the resulting distortions are small, even when the target plane is rotated around the pitch or yaw axis, as shown in Figure 5.

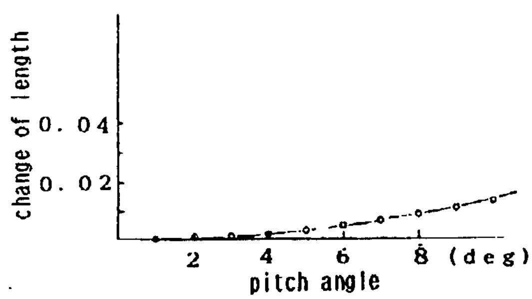

Figure 5. Changes in Side Length

Figure 5 shows amounts of changes in the length of the upper and lower sides of the rectangle formed by the four points projected onto the image plane when only the pitch angles are altered from the state in which the roll, pitch and yaw angles are zero, that is, when the target plane is facing squarely in the direction of the camera. The amounts of change are standardized by using the length of the side when the pitch angle is zero as the standard. A rotation of about eight degrees generates only a 1/100 change in the length of the side. This shows that it is difficult to obtain accurate pitch and yaw angles from the positions of the four points forming a rectangle within the image plane. In our sensor, therefore, a pole is erected in the center of the rectangle formed by the four-point marks perpendicular to the target plane, at the top of which is attached a fifth mark. Figure 6 shows calculations of changes in the distance between the fifth mark and the pole's root when the pitch angles are altered. The distances are those projected onto the image plane, and are standardized by using the length of the upper and lower sides of the rectangle when the target plane is facing the camera. As can be seen from the graph, the amounts of change are apparently larger than those shown in Figure 5. Since the position of the pole's root can be obtained from the four points on the target plane, the attitude of the target plane can be obtained with high precision.

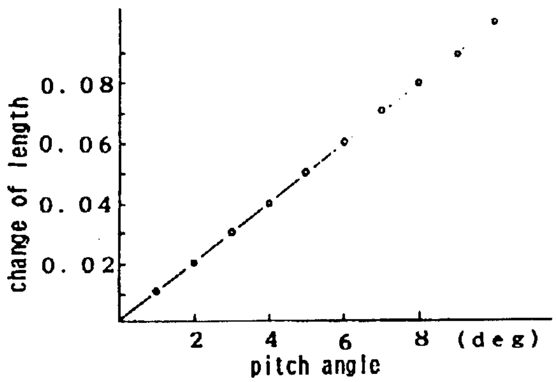

Figure 6. Changes in Pole's Length

4. Experimental Results

The system used in our experiment is shown in Figure 7 [not reproduced]. to facilitate the three-dimensional movements of the target, the axes of rotation for roll, pitch and yaw are provided on the X, Y and Z table. Each axis has a potentiometer for detecting the position and attitude of the target. By sending a command from the host computer, the measuring can be started or stopped.

Figures 8 and 9 show the high-precision measurements. Shown in Figure 8 are measurements obtained when the target is shifted in the direction of the Y-axis, corresponding to the direction of the camera's axis of light. Figure 9 gives the results of measurements taken when the axis of yaw is rotated 100 mm away from the camera. When the distance from the camera is 100 mm, the error is less than 2 mm in the X, Y and Z positions, while the error in the roll, pitch and yaw attitudes is less than ±2 degrees.

Figure 10 gives results of measurements taken of a moving target. The speed of the movement was about 10 mm/s, and the measured values were read from the host computer in 20 msec cycles. They clearly show the horizontal and vertical movements of the target.

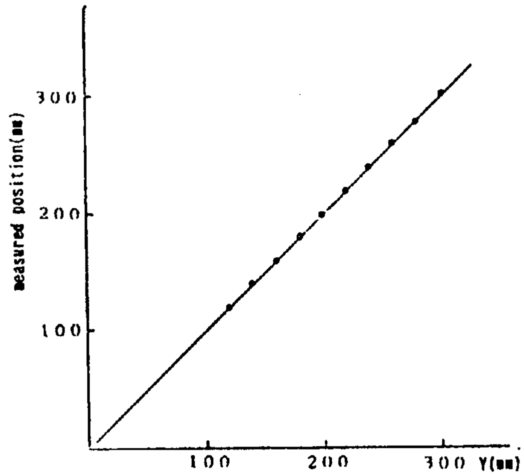

Figure 8. Position Measurement

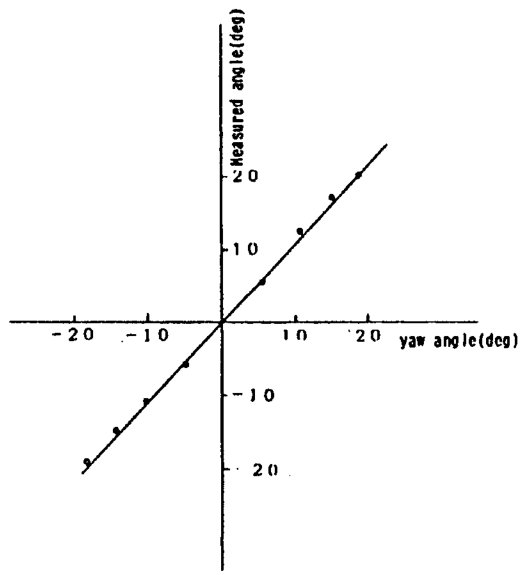

Figure 9. Orientation Angle Measurement

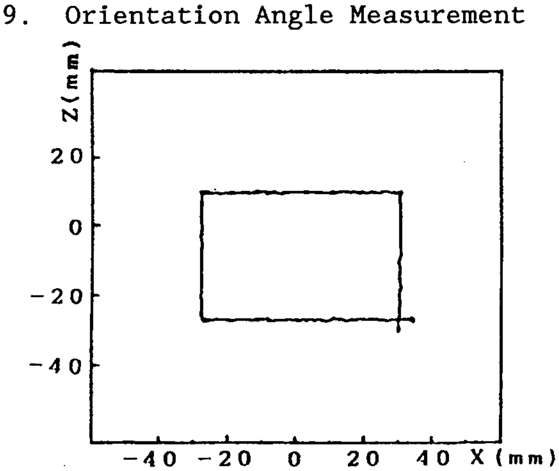

Figure 10. Measurement of a Moving Target Position

The calculation time needed for image processing is about 8 msec. However, since the camera's field frequency is 60 Hz, the measuring speed is 60 Hz.

5. Conclusion

In our sensor system, installing a target on the object to be observed has enabled the microprocessor system to detect the three-dimensional position and attitude of the object in real time at a measuring speed of 60 Hz. In order to improve the detection accuracy of the attitude of the object, the target is made up of a five-point mark, four marks of which are on the target plane and take the form of a rectangle, and one mark on the top of a pole erected perpendicular to the target plane.

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Visual Information Processing for Space Robotics

43062507d Tokyo PROCEEDINGS OF THE 2ND SAIRAS in Japanese 17-18 Nov 88
pp 55-57

[Article by Hiroshi Koyama, Eiichi Ogawa, Yukiko Yoshimoto and Norimasa Yoshida of Kamakura Works, Mitsubishi Electric Corp.]

[Text] 1. **Foreword**

For a space robot to be able to execute a complex operation accurately by adapting itself to changes in the work environment, it will have to be cognizant of the surrounding situation at all times. Obtaining knowledge of the kinds of objects existing within the work environment, of the relative positional relationships between the space robot and those objects and of the motion status of other robots is indispensable if the operation is to be executed smoothly.

Many methods of detecting information exist in the external world, but imaging is the best for obtaining the information existing within a broad expanse of space accurately and promptly.

Research involving visual information processing technology has been conducted in the fields of artificial intelligence and intelligent robots for a long time, and many visual information processing techniques have been proposed.

The practical use of the visual information processing technology necessary for executing various orbital operations in space has yet to be realized, however, and research into this technology has just now been initiated.

This paper describes the results of a study that we have undertaken to explore the possibility of observing the object targeted for observation by using an image sensor, which is the precondition for realizing visual information processing in space robotics.

2. Effects of Solar Light

If visual information processing for space robotics is to become feasible, the precondition is that the image sensor be capable of observing the object targeted for observation.

In other words, two conditions must be met: one is that there must exist a lighting condition that permits the robot's image sensor to recognize an image of the object; and the other is that the solar light not interfere with the functioning image sensor.

The above conditions are determined by the spatial relationship between the orbital plane of the robot's motion and the sun. In each case, it is preferable that the sun be located behind the robot and that the angle between the robot's speed vector and the sun's direction be small.

In general, the sun never remains behind the orbiting space robot at all times. As a space robot travels in its orbit, the relative position between it and the sun changes, as do the conditions under which the object appears for observation.

Furthermore, if an observation is to be made of an object that stays in the same orbital plane as the advancing space robot ahead of it, the angle between the orbital plane and solar light must basically be larger than the image sensor's interfering light avoidance angle.

For these reasons, when planning an orbital operation using a space robot, the correct selections of lighting conditions must be made with respect to the orbit, season and time.

3. Brightness of Observation Images

As a robot moves in its orbit, the relative positional relationships among the object to be observed, the robot and the sun undergo changes, as does the intensity of illumination of the object. Visual information processing begins with the processing of the observation images of the object that have been captured by the image sensor. Therefore, the brightness of the image created on the image sensor's photoreceptor must be greater than the sensor's sensitivity.

The object to be observed is, in general, illuminated by solar light and other light sources, so the observation image's properties are affected by properties of both the light source and the object. Again the object to be observed is a three-dimensional body, but the image obtained by the image sensor is a plain optical image formed on the sensor optics system's image-formation plane, so properties of the lenses also need to be taken into consideration.

Specifically, the intensity of illumination of an image formed on the plane of an image sensor's photoreceptor is affected by the intensity of illumination of the object to be observed, the reflectivity on the surface of the object, the transmissivity of the lens and the lens' F value.

Figure 1 shows the relationship among the intensity of illumination of the object to be imaged, the luminous radiance of the object, and the intensity of illumination of the image plane. Here, the transmissivity of the lens is assumed to be 0.8.

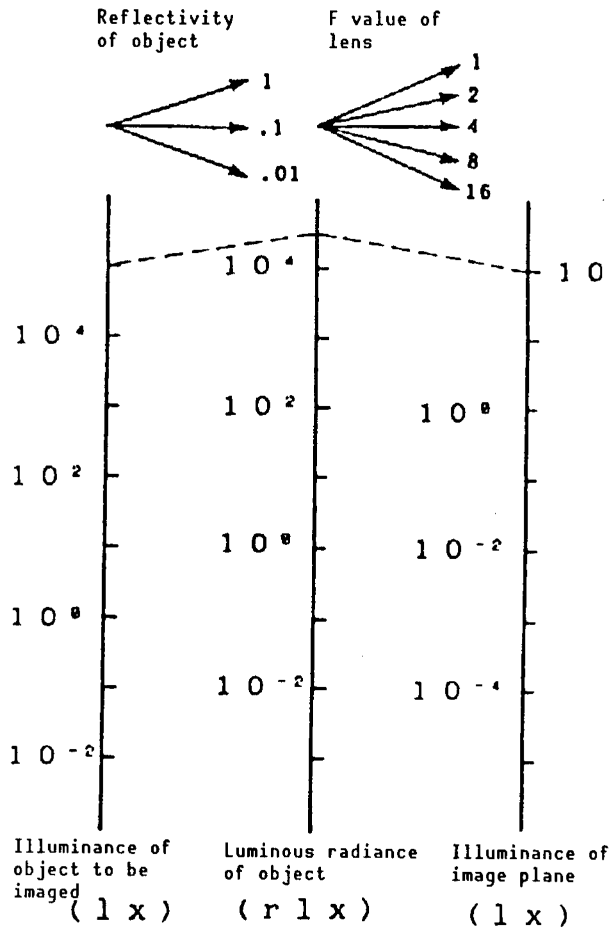

Figure 1. Intensity of Illumination of the Image Plane

The intensity of illumination of solar light in space is about 10^5 lux. Consequently, when observing an object of reflectivity of 0.32 using a lens with an F value of 8, for example, it can be determined from Figure 1 that the illuminance of the observation image on the plane of the image sensor is 100 lux.

The proper range of light quantities used is determined by the kinds of devices incorporated in the image sensor.

If the quantity of light is too much, the situation can be corrected by narrowing the lens opening. In some cases, it may be possible to reduce the quantity of light that passes through the lens by using an ND filter. If the quantity of light is insufficient, the situation is remedied by widening the lens opening, but additional illumination becomes necessary in some cases.

When using a CCD as an imaging device, the intensity of illumination on the image plane required for imaging is approximately 1 lux. When the intensity of illumination on the object to be imaged, the reflectivity on the surface of the object and the lens' F value are established, one can use Figure 1 to judge the practicability of observing the object to be imaged using an image sensor.

4. Effects of Illumination

If the intensity of illumination on the object to be observed is insufficient to permit the use of an image sensor, the object must be illuminated with additional lighting.

Figure 2 gives properties of the illumination light source (178 W) for the RMS shuttle.

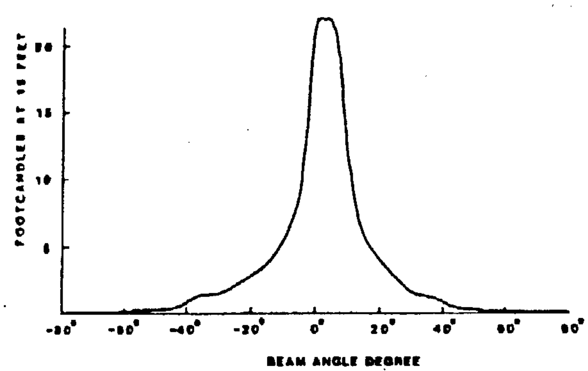

Figure 2. Properties of Flood Light for RMS

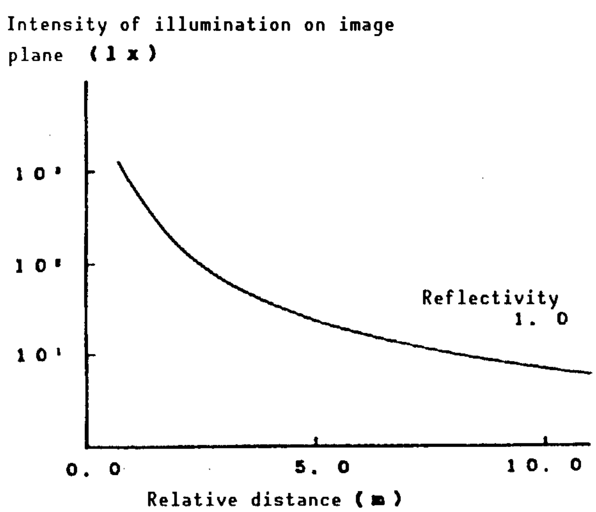

Figure 3. Effect of Illumination

In Figure 3, the relationships between the distance to the object and the intensity of illumination on the sensor's image plane are given. In this case, the lens' F value is 1.2, and the reflectivity on the object's surface is 1.

In this case, the relative distance at which the intensity of illumination on the image plane drops to 1 lux, the minimum level of illumination necessary for imaging using an ordinary CCD image sensor, is 30 m.

5. Conclusion

After images of the object to be observed have been obtained using an image sensor, they are subjected to image processing. Various methods of image processing have been studied, and can be classified into two categories: With one category of techniques, the information on the object is obtained by processing the image information itself, while with the other, a laser beam is directed at a reflector on the object or the surface of the object and the reflected light is caught, obtaining information on the object.

Neither method is practicable when the sun is within the view of the image sensor.

For highly reliable image processing, the images must have some levels of contrast.

Therefore, after taking into consideration the effects of solar light, the effects of illumination, the properties of the surface of the object to be observed, and the properties of the optics system and its relative attitude vis-a-vis the robot, it is necessary to evaluate, through simulations or experimental means, the characteristics of the observed images before the launch.

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Development of Fault Diagnosis Program for CS-3

43062507e Tokyo PROCEEDINGS OF THE 2ND SAIRAS in Japanese 17-18 Nov 88
pp 65-68

[Article by Kazuya Kaku, National Space Development Agency of Japan; Takeo Akashi, Mitsubishi Electric Corp.; Akira Yamauchi, Kazunori Suzuki and Yayoi Tanabe, Mitsubishi Space Software Co., Ltd.; Shinichi Kobayashi and Kosyu Kim, Mitsubishi Research Institute, Inc.]

[Text] 1. **Foreword**

In the near future, space will come to be used as an avenue for various activities. With it, the number of space vehicles will increase, followed by the diversification of the types of missions, and the tracking and control systems supporting the operations of those vehicles will face an increasing demand to meet the energy-saving, autonomous operation and high reliability requirements. Therefore, studies are being conducted to introduce knowledge information processing systems into those fields.

The development of this program, a prototype expert system for detecting abnormalities or diagnosing faults in a space vehicle, was begun in FY 1985 for the "series" Communications Satellite III (CS-3) for which there exists a rich accumulation of operations knowledge.

One of the developmental objectives of this program is to conduct technical evaluations of this type of expert system for its possible practical use in the future, and evaluations are being made of its adaptability to actual operations by using the actual flight data from the CS-3a and CS-3b launched in February and September 1988.

In this paper, we present an outline of this program, describe the problems that have cropped up during its development and our thoughts on how to solve those problems, and offer prospects for future systems.

2. Outlines of the Program

2.1 Major Functions

This program has the following functions. Figure 1 shows a conceptual configuration of these functions.

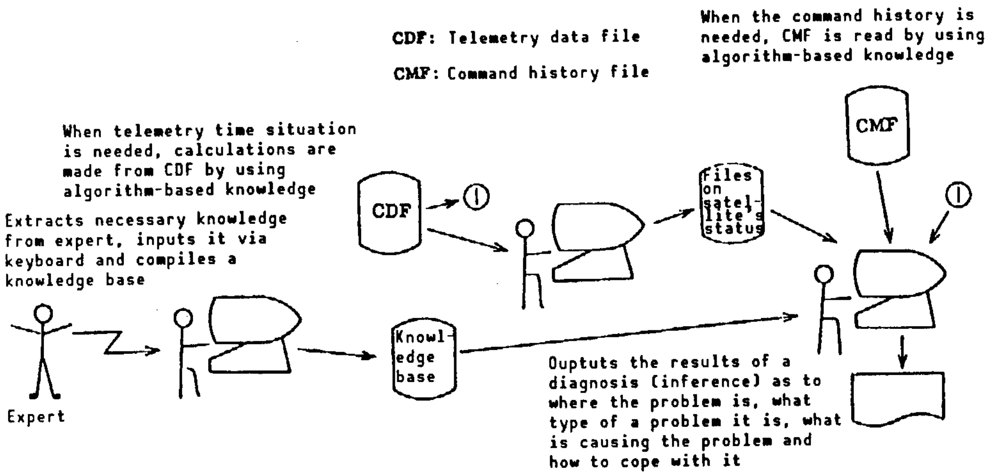

Figure 1. Conceptual Configuration of Functions

(1) Function enabling files to be compiled to indicate the state of the satellite

This capability enables files to be compiled indicating the status of the satellite using telemetry data gathered during a diagnosis.

(2) Function enabling motive state data to be input

This capability enables changes in the data with time and data trends to be analyzed and the results to be input.

(3) Abnormality detection and fault diagnosis function

This capability enables, by drawing on a knowledge database, any abnormalities existing in the satellite to be detected and, if so, to infer where the problem lies.

(4) Algorithm-based knowledge calculation function

This capability enables calculations to be conducted based on procedural knowledge (descriptions in FORTRAN) which are needed for abnormality detection and fault diagnosis.

(5) Function to display results of an inference

This capability enables the results of an inference (existence or nonexistence of any abnormalities or problems, and their contents) to be output in written form and graphic displays, indicating where the abnormalities or problems are occurring, to be generated.

(6) Function to provide an explanation of the knowledge base

This capability enables the process of inference and the contents of the knowledge base to be explained.

(7) Knowledge database compilation function

This capability enables gathered data to be turned into a knowledge database.

2.2 Hardware Configuration

This program was developed using a mainframe computer (FACOM M780) installed at the Tsukuba Space Center of the National Space Development Agency of Japan. The hardware configuration is shown in Figure 2.

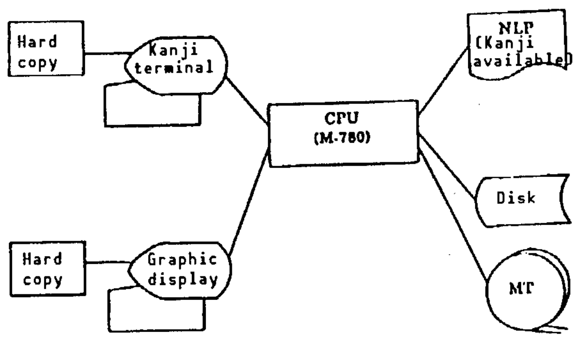

Figure 2. Hardware Configuration

2.3 Software Configuration

This program comprises three independent programs. Figure 3 gives the software configuration. Outlines of the functions of each program are given below.

(1) Program for compiling files on the satellite's status

By inputting the satellite data required to detect abnormalities or diagnose faults via the telemetry data file (CDF) or keyboard, this program enables a file on the status of the satellite to be prepared.

(2) Abnormality detection and fault diagnosis program

The abnormality detection and fault diagnosis program comprises the "knowledge generation support section" for inputting and editing the knowledge needed to make a diagnosis, the "fault diagnosis section" for inputting the file regarding the satellite's status, and the command history file (CMF) for making a diagnosis of the satellite, as well as the "explanation section" for displaying the diagnosis process and the knowledge contents.

(3) Program for displaying fault position

This program enables the fault position to be displayed graphically as well as the measures to remedy it.

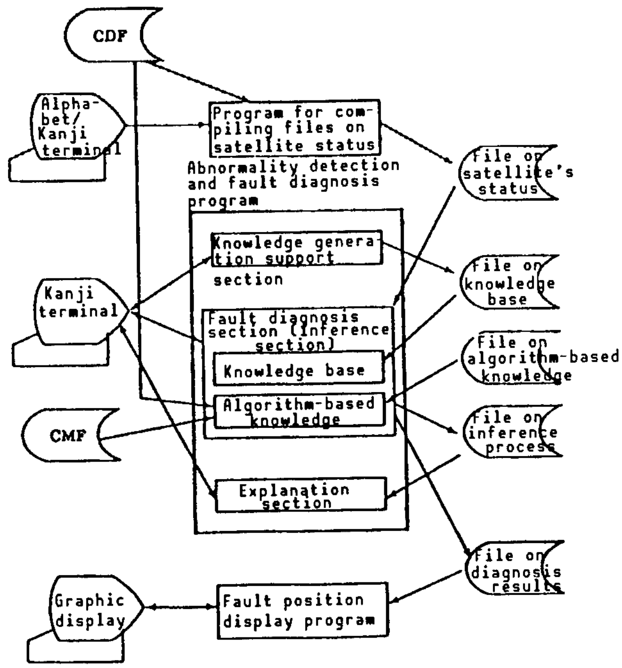

Figure 3. Software Configuration

2.4 Configuration and Knowledge Base

A knowledge base is a place where various kinds of knowledge necessary for performing such operations as abnormality detection or, fault spot inference, based on input data, is stored.

Four kinds of knowledge are handled in this program. They are: the context class tree that conceptually configures the process of an inference; the production rule that expresses judgment knowledge; the algorithm-based knowledge that shows numerical calculations and procedures of processing that are hard to express with the production rule; and the attributes that make up the data (hypotheses) handled by the production rule and algorithm-based knowledge.

The knowledge base currently in use was established based on the results of FMECA (failure mode effects and criticality analysis) of satellite subsystem components and the experience and knowledge obtained while operating the CS and CS-2, and is made up of independent subbases addressing each of the satellite's various subsystems. Figure 4 shows the knowledge base's construction, while Table 1 shows its scale.

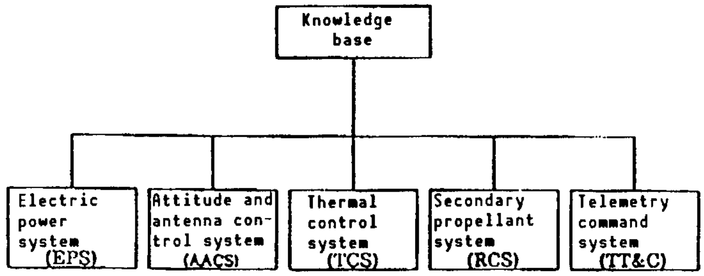

Figure 4. Construction of Knowledge Base

Table 1. Knowledge Base Scale

Subsystem	Number of rules	Number of attributes
EPS	372	238
AACS	158	142
TCS	487	255
RCS	52	52
TTC	18	14

This program also contains the following algorithm-based knowledge:

1) The position and angle of the sun
2) The position and angle of the moon and its brightness
3) Assessment of the shade and sunshine
4) Prediction of the electric power generated by the solar cells
5) Trends in the change with time in telemetry
6) Existence or nonexistence of command transmission

3. An Example of an Execution

Figure 5 gives an example of a case in which this program has been put to practical use. In Figure 5, the case is assumed in which, although no maneuvers have been undertaken, a drop in the tank pressure has been detected and a diagnosis is obtained based on the assumed data.

Assumed circumstances surrounding a malfunction

1. The propellant in the tank leaks from radial thruster No 1
2. No maneuvers have been conducted
3. The tank pressure drops 0.5 kg/cm^2 in 10 minutes

Knowledge base

Although no maneuvers have been undertaken

↓

Check the command history file

The trend pressure dropped more than 0.422 (kg/cm^2) in 10 minutes

↓

Seek trends in changes with time in telemetry

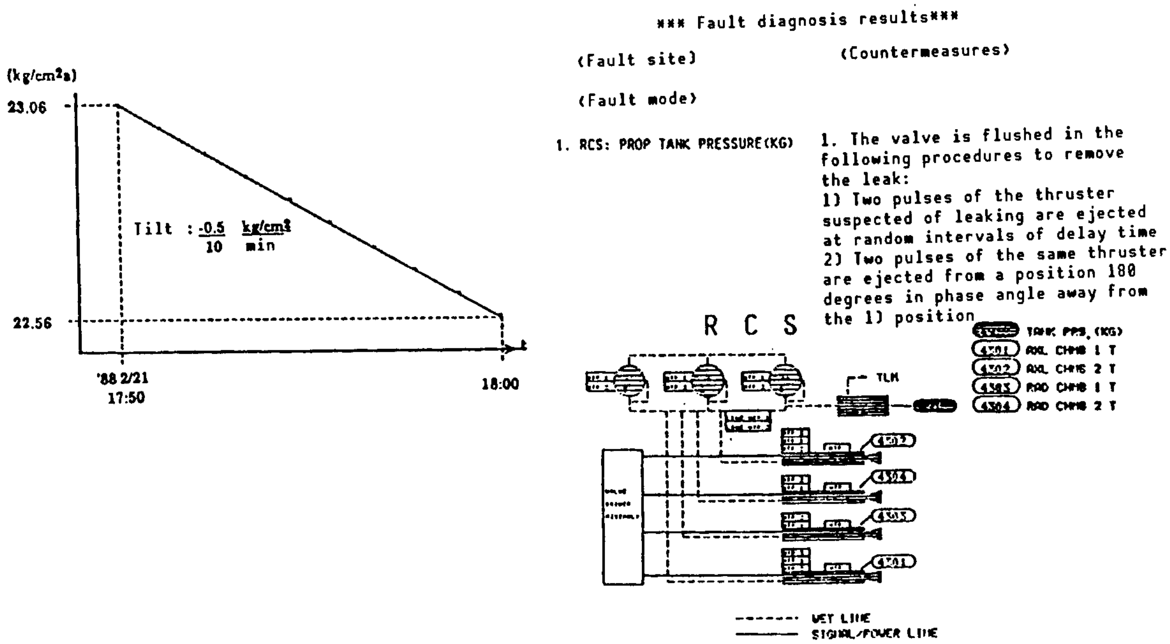

Figure 5. Example of Program Execution

4. Achievements in System Development and Future Prospects

The development of the current program has brought many achievements that will contribute to the future development of a practical system. The greatest achievement among them is the recognition that there is a fundamental difference between abnormality detection and fault diagnosis.

In other words, in a space vehicle designed with as much advance fault analysis as possible to prevent the occurrence of any such problems, the cases in which the vehicle is buffeted with a type of fault that can be easily inferred from the limited volume of data are extremely few, with the majority of problems arising from causes beyond even the imaginations of experts. Trying to address the problem involving "complications that cannot be expected in advance" with our system is, in principle, impossible unless it is provided with the design information, and this represents a significant problem when using it as a fault diagnosis system.

On the other hand, we believe that the function of abnormality detection, that is, detecting, based on previous data derived from the common sense of physics, experience and knowledge, a problem, although the specific problem is not known, can be fully realized as an extension of the current system technology by cleverly building a knowledge base incorporating the expert common sense and past experience.

Therefore, among the directions that will contribute to the practical use of such an expert system, a system having the twin functions of real-time abnormality detection and off-line fault diagnosis is being studied. As for the fault diagnosis function, we believe in particular that the utilization mode of expert systems, in which the computer provides hints on what is wrong so that the operator can diagnose the fault rather than autonomously diagnosing the cause of the problem on its own, should be studied as one option.

When the foregoing is taken into consideration, the current program is considered to involve the following six problems:

1) Depending on the case, the inference time (judgment time) is long, and this may give rise to a problem with when processing is to be done in real time.

2) It sometimes becomes necessary for the human being to answer questions, so the program cannot yet be totally automated.

3) Since no fully satisfactory explanation of the inference process (judgment process) has been given, no fully satisfactory evaluation of the results has appeared.

4) If the program is to be used for another spacecraft, partial amendments to the system (especially algorithm-based knowledge) are needed.

5) It is not easy to add new knowledge or revise existing knowledge (such as correlating with other knowledge items).

6) Since the system comprises several programs, its operation necessitates complex procedures.

Of the problems mentioned above, 2) is closely related to descriptions and the configuration of a knowledge base, and studies need to be made of methods for gathering and sorting knowledge. Items 3) and 5) are associated with tools for compiling expert systems, and we believe these problems can be solved in the future. Regarding 4), a conceivable solution would be to construct the system so that the knowledge contained would be comprised of general-purpose parts applicable to all space vehicles and exclusive parts specific to each spacecraft, but the problem requires further research. As for 6), we believe this problem can be solved by strengthening the computer environment and improving the software construction.

5. Conclusion

During our development efforts, we have learned that although existing knowledge information processing systems are not omnipotent, they can still be incorporated effectively into tracking and control systems. We plan to promote further research toward the goal of developing a practical system.

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Spacecraft Automatic Monitoring System

43062507f Tokyo PROCEEDINGS OF THE 2ND SAIRAS in Japanese 17-18 Nov 88
pp 69-72

[Article by Kazuya Kaku of National Space Development Agency; Takeo Akashi of Mitsubishi Electric Corp.; and Akira Yamauchi and Kazunori Suzuki of Mitsubishi Space Software Co.]

[Text] **1. Foreword**

Aiming at energy-saving, autonomous operation and high reliability of the tracking and control system, since 1985 we have been engaged in the development of "a fault diagnosis program for the CS-3," an expert system for abnormality detection and fault diagnosis for the communications satellite No 3 (CS-3). Having been drawn from the achievements obtained during the development of the fault diagnosis program for the CS-3, the spacecraft automatic monitoring system represents a trial system for the future practical use of such a type of system. This paper examines the requirements demanded of a practical system, its operation methods and its trial model.

2. Real Time Abnormality Detection System

2.1 Purpose of the System

When developing a spacecraft, fault analyses are carried out during the design phase and the results are incorporated into the design. Consequently, as long as the spacecraft is manufactured according to the design, the probability of its being buffeted with the kind of problems that can be anticipated is extremely low. As a result, if a malfunction on a spacecraft were to be observed, it would be very difficult to identify the cause and type of failure if one used only the knowledge employed for fault analysis at the time of the spacecraft's design. For the above reason, the reality in the effort to develop a "fault diagnosis program for the CS-3" was that the program was not able to cope with actual faults. On the other hand, we believe that the technology for judging whether the state of a spacecraft (telemetry, etc.) at a given time is normal not by drawing on the spacecraft's past state (data such as on or off status of the machinery and equipment, external environment, transmission commands, past history) is feasible. Furthermore, in order to cope with the dynamic movements of the spacecraft, it is necessary to catch data on any factor that may affect the spacecraft's state as soon as it arises and use this knowledge to infer the subsequent status of the spacecraft, so we consider important the function that enables information to be gathered in real time to detect abnormalities.

2.2 System Requirements

In realistic terms, a spacecraft automatic monitoring system must be equipped with the following functions:

(1) Operation support system

With the existing technology, it is impossible to tap every piece of human knowledge, and compile it into a knowledge base, and put it to use, so we believe the emphasis should be placed out on the complete unmanned operation of a spacecraft, but on the development of an operation support system that will alleviate the burden on the operator.

An operation representing a large burden is routine monitoring. This operation will not be called into action unless a change in the status of the spacecraft has occurred, but if such a change has occurred, for the operator to judge the change to represent a malfunction from routine monitoring would require that he be equipped with a high level of technology and much experience. Therefore, the automation of this function alone would greatly reduce the burden on the operator.

(2) Routine operation system

Since this system is designed to liberate the operator from the work involved in monitoring, monitoring needs to be conducted around the clock (in the case of a stationary satellite). Again, large amounts of data need to be processed at high speeds (in the case of an orbiting satellite). In the future, even an orbiting satellite will have to be monitored at all times due to the increasing number of link times with the data relay satellite.

For around-the-clock monitoring of a spacecraft to become feasible, information on the status of the spacecraft and its tracking and control system needs to be gathered in an on-line mode and processed in real time. Within the confines of the capability of replacing the operator, we believe that an abnormality detection speed on the order of minutes would suffice (excluding such exceptions as maneuvers). In terms of the capability of performing the same processing function continuously, a computer is more suited to doing the job than a human is, and the machine generates fewer oversights.

(3) Flexible operation

Assuming that the motions of a spacecraft and its tracking and control system can all be predicted during the design stage before the spacecraft's launch and that the need to alter the abnormality assessment or operation methods does not arise after the spacecraft has gone into service, then it is preferable that abnormality detection function be realized based on the existing type of programs (the algorithms are determined when the programs are designed). The reality, however, is that, for various reasons, alterations are usually made on the operation methods (operation procedures) and abnormality assessment standards. Furthermore, it is highly probable that new operation methods or judgment standards will be added. Consequently, a program's algorithms may be updated at any time, so it is necessary to respond to such an update quickly.

(4) Uniform quality operation

With the lengthening of the lifetime of a spacecraft, it is unlikely that the same operator will be operating the spacecraft for its entire life. Again, as the number of spacecraft increases, a spacecraft may not have an exclusive operator. In other words, when a spacecraft operation changes operator's hands, a change in the operation method, arising from the difference in the two persons' personalities, may ensue. One way of coping with such a situation would be to institute, by some means, ways of controlling the operation methods and judgment standards specific to individual spacecraft and to train the operators until they reach a certain level of expertise. However, it would take much effort to instruct all operators in the knowledge of the operation methods and judgment standards so that they would be able to cope with any emergency. Therefore, some operator support systems are awaited.

(5) How to cope in case of emergency

The main function of this system is abnormality detection, but it is desired that the system be equipped with the capability of taking emergency actions. When an abnormality has been detected by the system, the operator (or expert engineer) conducts a fault diagnosis in order to determine the location, kind and cause of the problem and studies what countermeasures to take. The contribution that this system can make in all this would involve gathering the types of information that may be required in order for the operator to make a fault diagnosis. This system may also be expected to perform such operations as transmitting commands in an emergency, as needed.

(6) System expansibility

Even when considering the lifetime of a spacecraft (several years), advances in technology may make it possible to build a system that is more effective and functionally sophisticated than the system currently being contemplated. Consequently, our system must be flexible enough to allow additions of new elements or revisions later.

2.3 Study of Operation Method

(1) Burden sharing

The type of system that we consider to be feasible will provide operation support in order to alleviate the burden on the operator. The scope of the role played by our system will expand as its accumulation of experience increases, but the best we can hope for now is a system offering abnormality detection capabilities.

(2) The burden on the operator

In the routine operation of a spacecraft, the operator must monitor the telemetry values at all times to see if any abnormalities are occurring. Letting our system take over this portion of the load will lead to a greatly reduced burden on the operator.

(3) Management of knowledge base, or revision of it

Depending upon the results of the operation of a spacecraft after it is launched, the need to revise the knowledge base may arise. However, before getting on with the work of revising the knowledge base, the knowledge must be confirmed, and after revisions of the knowledge have been made, the system is subjected to checks. Consequently, revision of the knowledge base will have to be undertaken within the framework of the management structure.

3. An Outline of a Trial Model

3.1 System Configuration

Figure 3-1 presents this system's hardware configuration, while Figure 3-2 shows its software. The hardware can be divided into two parts, while the software can be divided into three parts. The hardware comprises a personal computer that controls the simulator for the spacecraft and its tracking and control system, as well as the preprocessing of data, and an LISP machine that conducts abnormality detection based on the pretreated data. The PC and LISP machine are interfaced by an RS-232C. In other words, the PC takes over the function of the conventional software, while the LISP machine performs the role of the knowledge base system.

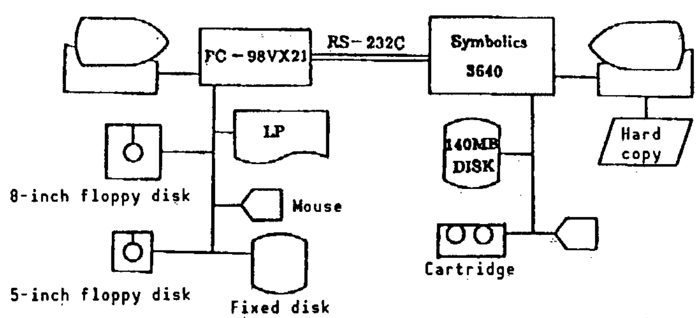

Figure 3-1. Hardware Configuration

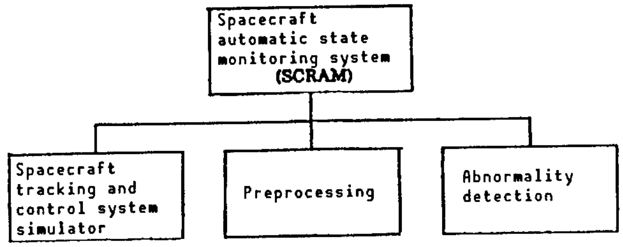

Figure 3-2. Software Configuration

3.2 Outlines of Functions

(1) Spacecraft and tracking and control system simulator

This enables the telemetry engineering values from the spacecraft to be simulated according to the preestablished data. It also displays the changes that the spacecraft undergoes in response to the commands transmitted.

(2) Preprocessing

By making comparisons with the judgment value obtained from the abnormality detection section, this function enables a judgment to be made as to whether or not the spacecraft is functioning normally. By performing statistical processing on the data, this function also enables changes with time of the engineering values to be plotted as an approximate curve.

(3) Abnormality detection

This function infers the standards for judging whether the spacecraft is functioning normally or abnormally from the results of the preprocessing and the status of both the spacecraft and tracking and control system, and transmits them to the preprocessing section.

3.3 Processing Algorithm

(1) Data analysis/engineering value judgment

In engineering value judgment, the predicted values are obtained from the predictive curve and an assessment is made as to whether the telemetry values are within the scope of normality. In data analysis, the coefficients are obtained based on the curve degrees, and standard deviations of the differences between the coefficients and predicted values are obtained. The conditions for the engineering value judgment and data analysis are given by the knowledge base. The knowledge base alters the conditions any time the results of the latest data analysis are obtained.

(2) Concept of engineering value judgment

In engineering value judgment, the scope of the upper and lower limits, within which the current value is considered a normal value, is deduced using the past data (data trends, commands transmitted, environmental conditions such as sunshine, shade, etc.), and a judgment is made as to whether the spacecraft is functioning normally or abnormally. Consequently, a comparison can be made at the same time the current value is input since the judgment standard already exists. This method has an advantage over the judgment method employed in the "Fault Diagnosis Program for the CS-3," in which a judgment is obtained following the input of the current value, in that the judgment can be expedited. Figure 3-3 shows the difference in engineering value judgment between the two methods.

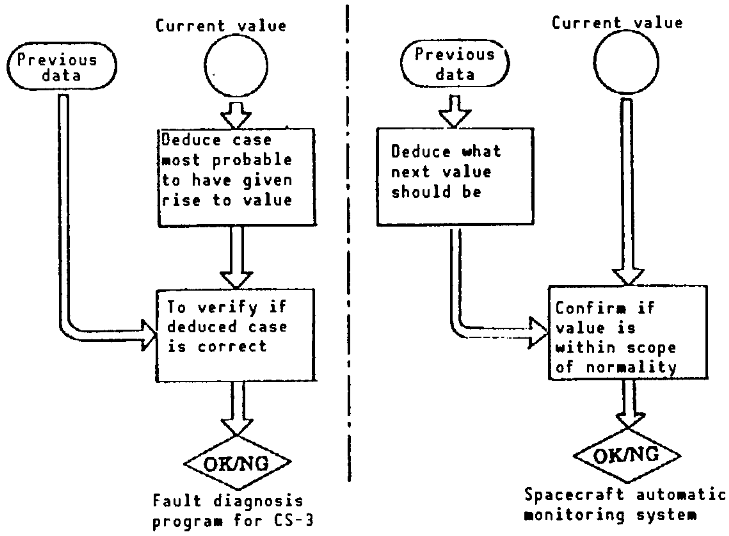

Figure 3-3 Difference in Engineering Value Judgment Between the Two Methods

4. Future Tasks

The spacecraft automatic monitoring system is intended for use in studying the technology necessary for building a goal system. In the goal system, necessary information is input from the tracking and control system, and after an abnormality has been detected, commands are transmitted if needed. The spacecraft automatic monitoring system on the other hand, simulates the spacecraft and the tracing control system. Figure 4-1 shows the relationship between the goal system and the spacecraft automatic monitoring system.

The future task involves how to get as close to the goal system as possible by learning from the spacecraft automatic monitoring system. Specifically, the following items are being studied:

(1) Study of abnormal cycle time
(2) Study of the inference method appropriate for the system
(3) Study of the method of gathering of knowledge
(4) Study of the common use of the knowledge base
(5) Study of man-machine interface

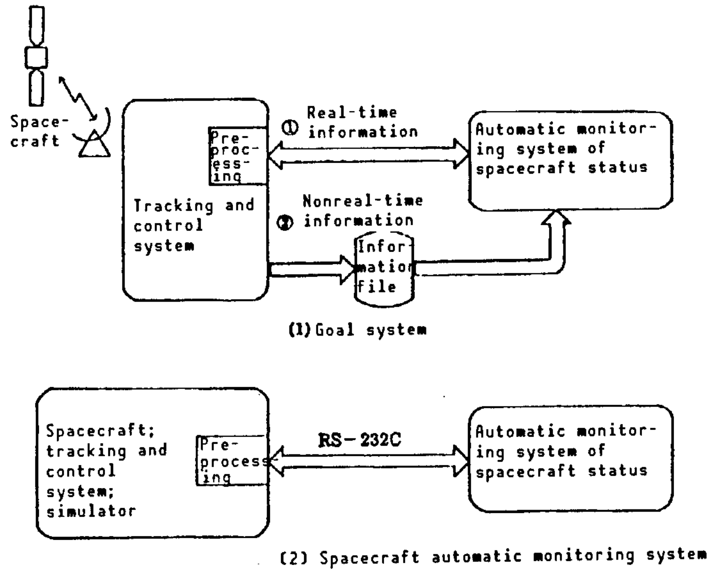

Figure 4-1 Goal System and Spacecraft Automatic Monitoring System

5. Conclusion

As space activity increases in the future, the demand for human-support systems is also expected to increase. The spacecraft automatic monitoring system has demonstrated the potential (knowledge base system) for use in realizing such a system. We plan to release a trial model of this system within the year.

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Autonomous Space Robot, Related Computer Systems

43062507g Tokyo PROCEEDINGS OF THE 2ND SAIRAS in Japanese 17-18 Nov 88
pp 93-96

[Article by Toshio Okamoto, Kenji Hiraishi, Haruki Ayada and Noriko Terada, NEC Corp.]

[Excerpt] 1. **Foreword**

In view of the specific nature of space activity, the development of highly autonomous robot systems is awaited for use as robot systems to be employed in space. While robot systems with high levels of autonomy are being developed, partially autonomous robot systems can be thought of as constituting one mode of such systems.

Here, we have tried to identify the autonomous levels of robots and have examined the configuration and functions of computer systems for a partially autonomous robot system. The results are described in this paper.

2. Autonomous Levels

A robot's autonomy refers to the capacity of the robot to carry out a given mission independent of a human.

For the autonomous control of a robot to be realized, strengthening its intelligence capability, equivalent to the brain and motor nerve of man, and upgrading its motor functions are indispensable. The former is the problem-solving capacity, i.e., the capacity to identify a method for carrying out a given mission, while the latter is the capacity to carry out that mission.

Table 1 gives intelligence levels and autonomous function levels of robots. In the table, the robots are stratified into playback robots, sensory robots, knowledge robots and intelligent robots, in descending order of intelligence.

A playback robot carries out the motions previously taught to it by a human, and it cannot cope with changes in its environment. Consequently, a playback robot can execute autonomously only certain missions, such as routine and fixed-type missions, of a level at which the procedures for mission execution

Table 1. Intelligence and Autonomous Levels of Robots

<u>Intelligent robots</u>	
Intelligence level:	Strategy, learning, inference, evaluation, understanding the environment
Required functions:	High-level coordination control, learning-type knowledge base, optimal redundancy control
Autonomous capabilities:	Is capable of solving, on its own, unknown or unexpected events; is capable of autonomously executing nonroutine and dynamic missions
Autonomous level:	Fully autonomous
Human participation or help:	Commands are given as to what missions to perform; advice is given as needed
<u>Knowledge robots</u>	
Intelligence level:	Planning, selection, judgment, probing, identification of an object, recognition of the environment
Required functions:	Mid-level coordination control, teaching-type knowledge base, redundancy control
Autonomous capabilities:	Is capable of solving, in its own, events of which the robot has prior knowledge; is capable of executing autonomously routine missions and some levels of nonroutine missions
Autonomous level:	Fully autonomous
Human participation or help:	Commands are given as to what missions to perform; how the mission is being executed is monitored and confirmed; commands are given if events that the robot has yet to experience occur; teaching of knowledge
<u>Sensory robots</u>	
Intelligence level:	Sensing, correlation, identification of the object
Required functions:	Adaptive control, compliance control, impedance control, low-level coordination control
Autonomous capabilities:	Is capable of acting according to instructed procedures based on prearranged control rules; is capable of adaptive motions with the help of sensors; is capable of autonomously executing routine and dynamic missions

[continued]

[Continuation of Table 1]

[Continuation of Sensory robots]	
Autonomous level:	Partially autonomous
Human participation or help:	Commands are given for procedures; the action must be monitored and the results confirmed; handling emergencies and resetting
Playback robots	
Intelligence level:	Memorizing
Required functions:	Sequence control, numerical control
Autonomous capabilities:	Is capable of acting according to instructed procedures based on prearranged control rules; is capable of autonomously executing routine and fixed missions
Autonomous level:	Human control
Human participation or help:	Compilation of operation programs; monitoring of operational changes; confirmation of the results

have been determined in advance and when no changes in the object to be worked on and the environment occur.

A sensory robot is provided with an external and an internal environment sensor. It is of an intelligence level at which, by processing the sensor data and feeding it to the control system as feedback, the robot can autonomously carry out routine and dynamic missions when the parameters of the workpiece and work environment change within the scope of certain fixed procedures.

In addition to being capable of coping with routine and dynamic missions, a knowledge robot is at a level at which it can cope with routine and dynamic missions that are within the scope of being "soluble," by drawing on the knowledge given to it in advance.

A still further sophisticated robot, an intelligent robot, has the capacity to solve problems belonging to yet unknown phenomena, and is at an intelligence level that enables it to cope with undefined and dynamic missions.

Simulations of space robots address such operations as the construction of large structures, ORU exchange, examining the spacecraft from the outside, docking, and towing of platforms. Each of these activities requires routine and nonroutine operations. Consequently, the type of operation assigned to a specific space robot will have to be determined by taking its autonomous level into account.

3. Studies on Partially Autonomous Robots

Figure 1 gives an example of the configuration of a partially autonomous robot system on the level of a knowledge robot. The partially autonomous robot system is made up of the motor function system, local AI, main AI, man-machine interface and external information system interface. Explanations are given below, according to intelligence and autonomous levels, using Figure 1.

(2) Sensory robot level autonomous system

First, in partially autonomous robot systems on the sensor robot level, the priority is the autonomous operation of the motor function system. The autonomous operation of the motor function refers to the real-time processing of such controls as compliance, impedance, low-level coordination control and a collision-avoidance function that enable the robot to cope with dynamic missions, as well as that of the high-performance actuators, sensors and sensor data that make those controls possible.

As for the mode of the system, it possesses only the motor system and man-machine interface section shown in Figure 1, and the two are directly linked. I/F with the local AI, main AI and external information system is conducted by a human for the robot system.

Space robot systems of a telepresence/teleoperation mode also are found on this level of robots. The autonomous control of these motor function systems is expected to greatly increase the operator's ease of operating a robot.

(2) Partially autonomous systems of the low-level knowledge robot level

Among the robot systems on the level of low-level knowledge robots are those equipped with local AI.

Local AI is designed to initiate the autonomous control of the processing of the low-level knowledge directly connected to the motor function systems. Local AI comprises a local knowledge base and a compact interpreter.

In addition to being equipped with the basic knowledge of the actuator control rule, sensor control rule, abnormality detection rule, and the operation rule at the time that an abnormality is detected as the basic operation knowledge, the local knowledge base also contains data on the robot's internal environment as partial environmental knowledge, data on the external environment within the scope directly related to the robot operation, and data on the object to be worked on. Through knowledge base control systems, the local knowledge base rewrites and controls the knowledge in a coordinated way.

The compact interpreter consists of an operation generation system, an environment recognition system and their execution control systems.

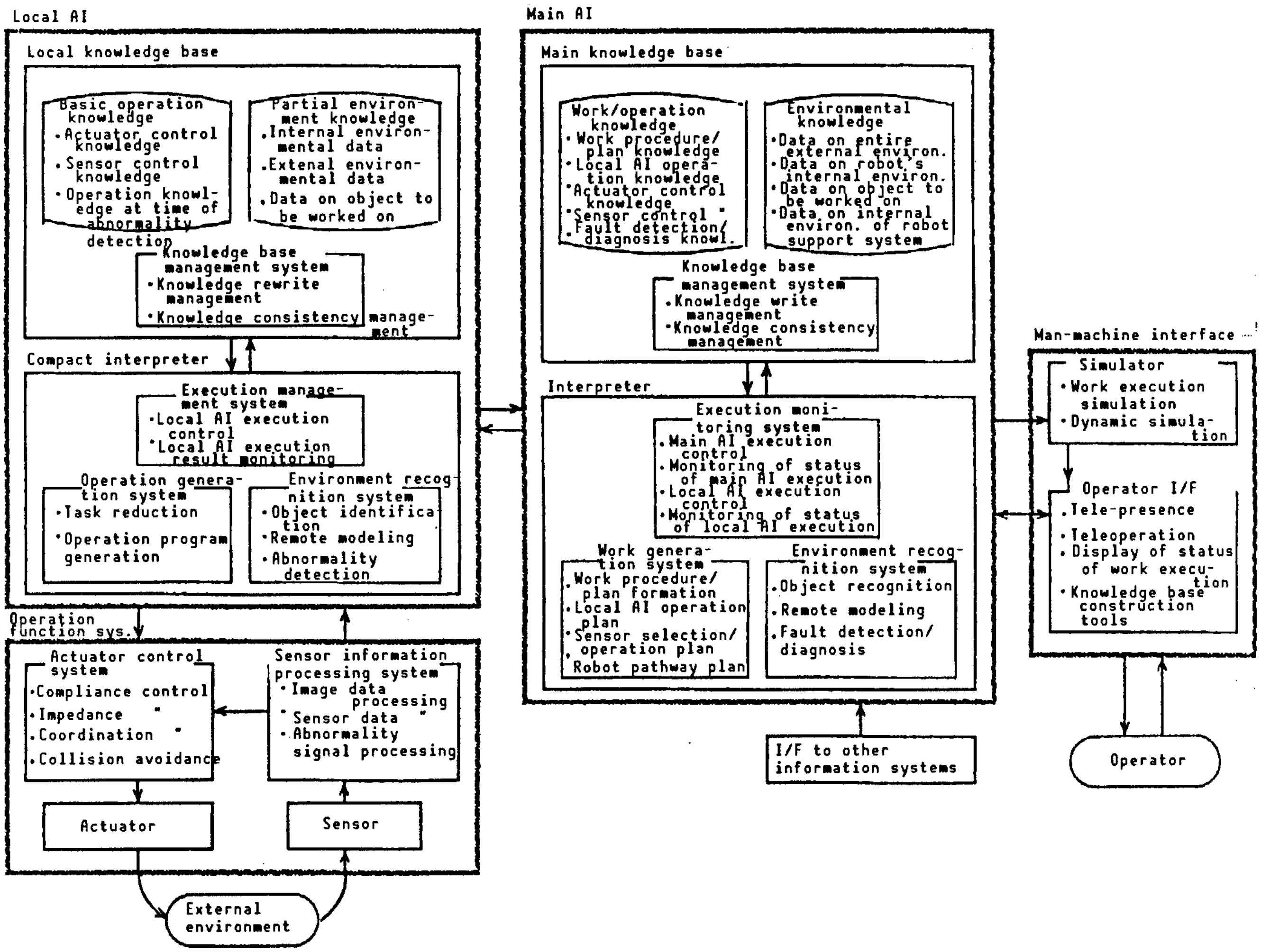

Figure 1. Example of a Partially Autonomous Robot System Configuration

Drawing on the preprocessed sensor information and the environmental knowledge contained in the knowledge base, the environment recognition system identifies the object to be worked on, detects abnormalities and conducts low-level world modeling.

In the operation generation system, based on task-level work instructions the routine work is broken down into basic operations appropriate for the prevailing environment by drawing on the knowledge base, programs for the sensor and actuator controls are generated, and the motor function systems are ordered to execute operations according to the programs.

The execution control system controls the execution of operations in the operation generation and engineering recognition systems, and monitors the results of the operations executed. It also acts as a window for interfacing with a person or higher level intelligent systems.

At this level of autonomous systems, the knowledge for the local AI is selected and is systematically taught by a person.

(3) Higher hierarchy knowledge robot level partially autonomous systems

Furthermore, a knowledge robot system higher on the hierarchy that would incorporate the main AI and an interface to the external information system is being studied.

The main AI consists of the main knowledge base and an interpreter.

The main knowledge base handles a broad field of knowledge addressing the entire operation and the environment. Regarding knowledge pertaining to work and operation, the main knowledge base contains knowledge for how to compile the work procedure plan and how to operate the local AI, as well as for sensor control, actuator control, fault detection, and fault diagnosis. Regarding the knowledge of the environment, it contains data on the external environment as a whole, data on the environment inside the robot, data on the series of objects being worked on, and environmental data on the man-machine interface and interfaces to external information processing systems.

The interpreter of the main AI performs the following tasks: a work plan is compiled using knowledge contained in the knowledge base, which is further divided into task levels, and the knowledge required by the local AI for operation execution is selected from the knowledge base and is offered for use. It also monitors and controls the local AI's execution and evaluates the results of the execution upon completion by comparing the results to the entire work schedule.

The interfaces to the external information systems enable the automatic forwarding and receiving of environmental data to and from systems other than the space robot system, e.g., the control system aboard the space base, to be accomplished.

At this level of sophistication, if a work mission is assigned, the robot is capable of autonomously executing routine dynamic operations and nonroutine dynamic operations using knowledge.

4. Task for Realization

Described below are tasks that need to be overcome if these partially autonomous robot systems are to be realized, as well as computers that must be developed.

Computers required if the motion function systems are to be controlled must process, in real time, large amounts of data, such as the repetition of coordinate transformations and the extraction of features from image data, in both the actuator control system and the sensor information processing system. These computers must be equipped with the capabilities to perform high-speed floating-point computations and high-speed processing of high-level functions, and consequently, the development of digital signal processors, general-purpose high-speed processors and processors to be used exclusively for image processing is awaited.

The local AI must process knowledge in real time in close coordination with the motion function systems, so it must be capable of high-speed knowledge processing. The tasks in this field are the development of data flow machines and reduction machines to realize high-speed operation by parallel processing, and multiprocessor system computers, as well as the development of high-speed knowledge processing methods, methods for constructing knowledge bases and management and control methods.

Since the main AI handles a broad scope of knowledge, the tasks there include the development of methods to display knowledge and of methods to efficiently renew large knowledge bases. In the interpreter field, the task involves the development of high-level processing methods of such knowledge elements as planning, evaluating and probing. [Passage omitted]

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Simulator System Developed for Use in Space Retrieval Experiment

43062507h Tokyo PROCEEDINGS OF THE 2ND SAIRAS in Japanese 17-18 Nov 88
pp 103-106

[Article by Haruhiko Shimoji, Masao Inoue and Kazuo Tsuchiya, Mitsubishi Electric Corp.; K. Ninomiya, Ichiro Nakatani and Junichiro Kawaguchi, Institute of Space and Astronautical Science: "The Development of Simulator System for Space Retrieval Experiment"]

[Text] **1. Foreword**

In developing a manipulator system for use in a satellite retrieval experiment and in evaluating its performance, we must give consideration to the motion of the satellite itself which is caused by the motion of the manipulator. With this in mind, we have been developing a ground simulator that simulates the state of nongravity. This simulator system has roughly attained the level at which it can be used as a tool for the development of a manipulator system, so we subjected the simulator to an experiment to measure the accuracy of its space environment simulation.

Described below are the simulator's system configuration, simulation algorithms, and results of the experiments conducted to evaluate the system's performance.

2. System Configuration

In Figure 1, the external appearance of the system is shown, while Figure 2 gives the construction of the computer system. The computer system is made up of three independent computers which control the entire simulator, the manipulator and image processing, respectively, and these computers can communicate with one another. In each computer, the 68020 and 68881 machines are combined for use as the main calculator, with a CPU serving as the lower hierarchy processor.

2.1 Simulator Section

The simulator section consists of a manipulator mount, that is supposed to be an SFU (space flyer unit) and moves up and down, and a gimbal table that simulates a TU (target unit) and is capable of translational movements

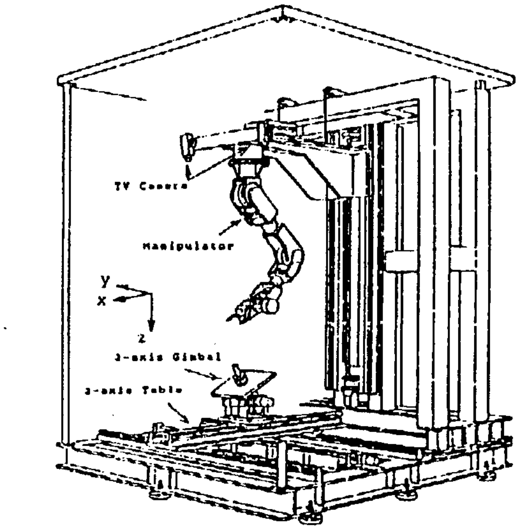

Figure 1. Six-Axis Simulator System

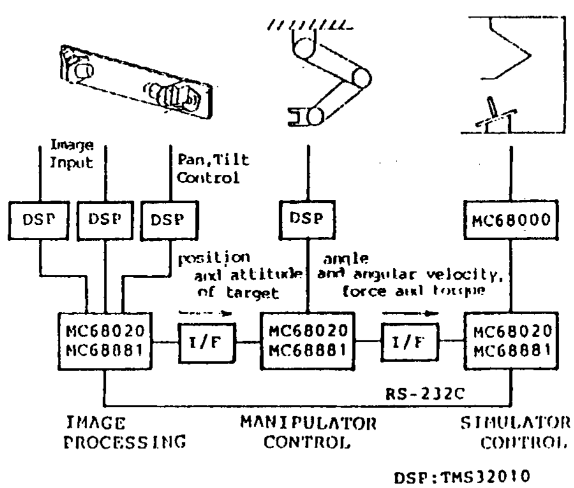

Figure 2. Block Diagram of the System

forward and backward, and right and left, as well as of rotational movement around a three-axis shafting.

Using data input from the actual system and the mathematical models contained inside the calculators, the SFU and TU movements in space are calculated based on the algorithms described in the following paragraph, and their relative positions and attitudes are simulated in the system.

The initial stage conditions of the SFU, TU and manipulator, such as masses or inertial moments, initial stage positions and attitudes which are maintained as mathematical models, can be changed with ease, so experiments can be conducted under various simulated environments.

Calculations of the relative positions and attitudes are conducted using the 68020 machine at a speed of 50 msec, and servos with six degrees of freedom are processed in parallel using the 68000 machine.

2.2 Manipulator Section

A multiarticulated arm with seven degrees of freedom and measuring about 1 meter in total length, the manipulator is an improved version (1 degree of freedom has been added) of an arm developed for use in vacuum testing. Simple in its mechanism, the hand is of a three-finger opening and closing type, making it easier to grasp the TU. Regarding the control system, as shown in Figure 2, it is constructed so that the orbits of finger-tip coordinates are established using the 68020 machine, and are converted in the DSP (32010) into angular velocity commands to the joints. Using the data on the TU position and attitude sent from the vision processing system, the finger-tip coordinate commands calculate the orbit that will enable the TU to be approached smoothly. Calculations of the orbit take from 3~10 msec, while those of the articulated servo take about 1 msec, and these calculations are processed in parallel.

2.3 Vision and Recognition Section

An image obtained by an infrared LED mounted on the TU is input via an infrared transmissivity filter, using two CCD cameras, and the relative position and attitude of the TU vis-a-vis the SFU are obtained. LEDs are positioned at the four corners of a square with sides of 26 cm. The cameras are installed 35 cm in front of the manipulator mount, 70 cm away from one another. The cameras rotate around a two-axis shafting and are capable of coping with large translational movements of the TU.

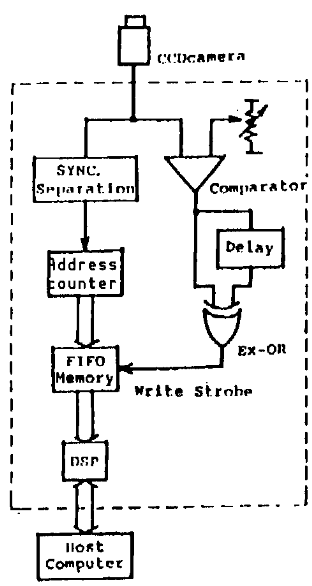

Figure 3. Block Diagram of Image Input Circuit

For inputting images, the exclusive processing system shown in Figure 3, which is based on a method in which the hardware extracts only the addresses of edges and writes them into memory, is used. This improvisation has enabled the number of input data to be reduced to about 50 data/image items, and the processing time to be shortened.

In order to estimate the position and attitude of the TU, a trigonometric survey method using two eyes and a method based on the LED layout pattern are used concurrently, with the calculations conducted in the main calculator. A 68020 machine is used as the main calculator, with a DSP (32010) used for image input and directional control of the cameras.

3. Simulation Algorithms

After the movements of the SFU and TU have been solved independently, they are converted into relative position and attitude. Since the movements of the TU are equivalent to those of the SFU minus those of the manipulator, only the movements of the SFU are described below.

The principle involved is that the momentum of the entire system, including that of the manipulator, is conserved when there is no external force working on it. In cases in which external forces are working on the system, these forces are numerically integrated to transform them into momentums, which then come under the control of the rule of conservation of momentum. In this way, these cases can be treated in the same way as when no external force exists.

The input from the simulator system includes the joint angle θ and joint angular velocity $\dot{\theta}$ (θ is numerically differentiated) of the manipulator, as well as the output of the torque sensors mounted on the manipulator's wrist and on the lower side of the TU's handle.

The basic formulas are the law of conservation of momentum and the law of conservation of angular momentum

$$L = \sum_{j=0}^{7} m_j \dot{r}_j \tag{1}$$

$$M = \sum_{j=0}^{7} (I_j \omega_j + m_j r_j \times \dot{r}_j) \tag{2}$$

where L is momentum, M angular momentum, and I_j, w_j, m_j and r_j the inertial tensor, angular velocity, mass and the center of gravity position vector, respectively, for each link. The subscript, however, shows the number of the link, and the SFU itself is considered to be the zero-numbered link. Here, using F and N input from the force/torque sensors, L and M are renewed successively.

$$L\ (t + \Delta t) = L(5) + F\Delta t \tag{3}$$

$$M(t + \Delta t) = M(t) + N\Delta t + r_f \times F\Delta t \tag{4}$$

where r_f is the vector indicating the point on which F and N are working.

The velocity $\dot{r}_j$ and angular velocity w_j of each link of the manipulator can be expressed as follows by using the velocity $\dot{r}_0$, angular velocity w_0 and the rotation speed of each joint $\dot{\theta}_j$ of the SFU proper:

$$\dot{r}_j = \dot{r}_0 + \sum_{k=0}^{j-1} (\omega_k \times b_k + \omega_{k+1} \times a_{k+1}) \tag{5}$$

$$\omega_j = \omega_0 + \sum_{k=1}^{j} \dot{\theta}_k z_k \tag{6}$$

Here, a_k is the vector from the k-numbered joint to the center of gravity of the k-numbered link, b_k is the vector from the center of gravity of the k-numbered link to the (k + 1)-numbered joint, and z_k is the unit vector in the direction of the joint's axis of rotation.

From equation (1), the center of gravity velocity $\dot{r}_g$ of the entire system can be expressed as

$$\dot{r}_g = \frac{L}{\sum_{j=0}^{7} m_j} \tag{7}$$

while from equations (2), (5) and (6), w_0 can be summarized as

$$\begin{aligned}\omega_0 = &\frac{1}{\sum_{j=0}^{7} (I_j - m_j [r_j][r_{0j}])} \\ &[M - \sum_{k=1}^{7} (\sum_{j=k}^{7} I_j) z_k \dot{\theta}_k - \sum_{k=1}^{7} m_k r_k \times \sum_{j=1}^{k} (\dot{\theta}_j z_j \times (r_{jk} + a_j)) \\ &- (\sum_{j=0}^{7} m_j r_j) \times \dot{r}_0]\end{aligned} \tag{8}$$

but,

$$r_{jk} = r_k - r_j$$

$$[r_j] = \begin{bmatrix} 0 & -r_{jz} & r_{jy} \\ r_{jz} & 0 & -r_{jx} \\ -r_{jy} & r_{jx} & 0 \end{bmatrix}$$

When considered based on the center of gravity fixed coordinate system for the entire SFU, w_0 can be obtained

$$\sum_{j=0}^{7} m_j r_j = 0$$

when using w_0 and $\dot{r}_g$,

$$\dot{r}_0 = \dot{r}_g + w_0 \times r_{g0} \tag{9}$$

By integrating w_0 and $\dot{r}_0$, coordinate transformation determinants to r_0 and the inertial coordinate system are obtained. Similarly, when position/coordinate transformation determinants are obtained for TU, they are converted into positions and attitudes to control the simulator system.

In conducting the aforementioned calculations, in order to accelerate the calculation process, we studied a simplified manipulator model in which the manipulator section is composed of a monolithic rigid body extending from the elbow to the wrist. This is based on the following assumption that since, in a space manipulator, there is no need to support one's own weight, the link section can be lighter in weight and, as a result, while the majority of the mass of the manipulator section comes from the actuators in the joints, slight inertial changes are brought about by rotations of the wrist joint.

4. Evaluations

In order to confirm that the space environment can be simulated accurately on our simulator system, we conducted two kinds of experiment: one involved a case in which the manipulator was in contact with the TU, while in the other the manipulator was not in touch with the TU.

4.1 A Case in Which the Manipulator Moves Freely in the Space Environment

From the state in which the SFU, TU and manipulator were standing still, the manipulator finger was moved 18 cm in the x-axis direction on the SFU fixed coordinate system and then brought to a stop. Masses of the SFU proper and the manipulator section were 2,022 kg and 95 kg, respectively, and the distance between the center of gravity for SFU and that of TU was 60 cm. We measured the relative positions and attitudes appearing directly on the simulator system.

Results of the experiment are given in Figure 4. The graph shows an ideal path with no time lag and the actual path. As the manipulator moves, the SFU is subjected to a translational motion in the x and z directions and a rotary motion around the y-axis. Because of the time necessary for calculating and solving the motions and because of the inertia of the equipment itself, a time lag of some 100~150 msec is generated giving rise to errors in the position and attitude. However, when we compare them to the errors occurring during visual recognition, these errors are believed to be small and thus within the allowable limits. The experiments have confirmed that the behavior of the SFU resulting from a free-moving manipulator can be simulated by the simulation system.

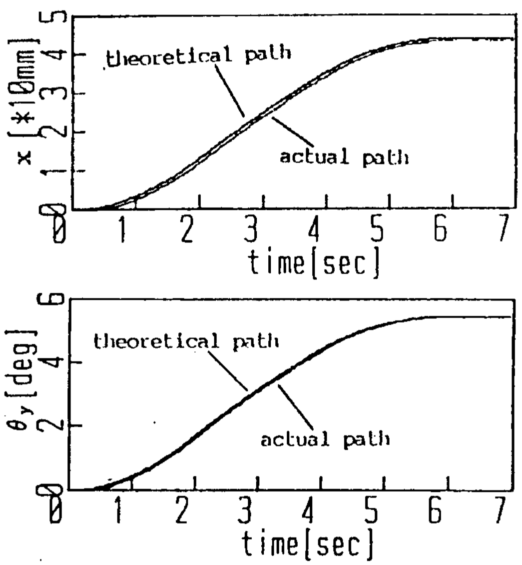

Figure 4. Behavior While the Manipulator and Target Are Not in Contact

4.2 A Case in Which the Manipulator Moves While Maintaining Contact With TU

The behavior of the manipulator at the time when it actually collides with the TU is complex since both the SFU and TU are subjected to external forces, therefore, in our experiment, we examined the behavior of the TU in a simplified scenario in which, traveling at a fixed speed, the TU bumped into a fixed obstacle. In the experiment, the TU was moving in the x and y directions at speeds of about 1.5 cm/sec, and its handle section collided with a bar-shaped obstacle installed parallel to the y-axis. The TU weighed 70 kg.

Figure 5 gives the results of the experiment. Changes in the force that the obstacle imparts to the TU at the time of collision are input from the force sensor. By integrating the force and solving the rule of the conservation of momentum, motions similar to behaviors that would generally be expected in a collision, such as the motion of rebound in the x-axis direction, deceleration in the y-axis direction, and the rotary motion around the y-axis, can be simulated on this simulator system.

The experimental results have confirmed that the behavior at the time when the manipulator and TU collide and the force/torque between the two is in force can be simulated in the simulator system by incorporating into the simulation program the external force in the form of momentum.

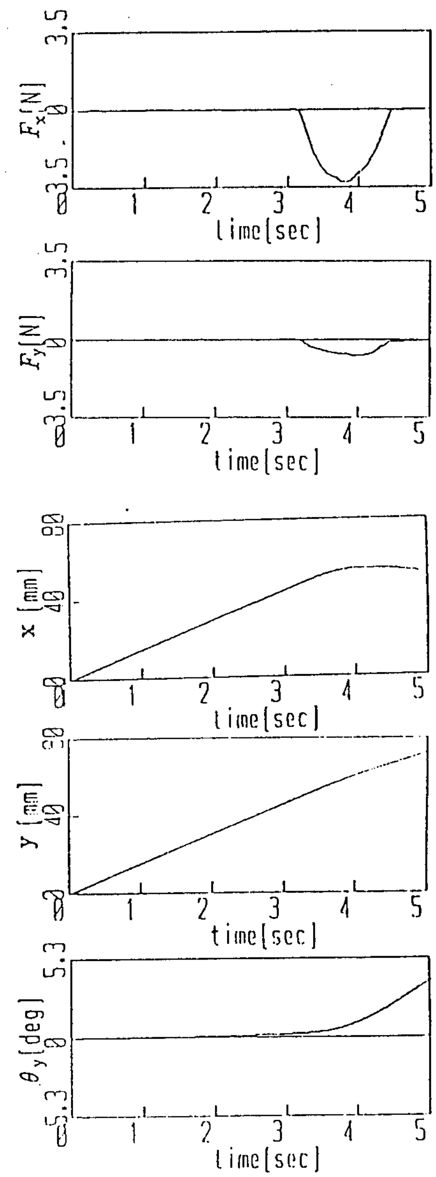

Figure 5. Force and Behavior When the Target Collides With the Obstacle

5. Conclusion

In the foregoing we have described the simulator system as applied to a space retrieval experiment and the results of our experiments.

Using this system, we are now conducting research involving recognizing the motion of a high-speed TU using an exclusive image processing system, controlling the space manipulator by drawing on image information and the TU capturing method.

We are also studying how to speed up the calculation function of the simulator so that it will be capable of coping with high-speed and high-precision simulations.

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DSP-Based Numerical Calculation Engine Application in Advanced Robot Controller

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pp 115-118

[Article by Nobuaki Takanashi and Norio Tagawa of C&C Systems Research Laboratories, NEC Corp.; and Takanori Ikeda of NEC Scientific Information System Development, Ltd.]

[Text] 1. **Foreword**

The demand for the autonomous operation of robotic works is high in the case of space robots. In promoting the autonomous operation of robots, the technology for the real-time simulation of the static and dynamic characteristics of an arm with multiple degrees of freedom and sophisticated-control methods that will enable the smooth execution of fit or copy operations using force information are needed. If such control methods are to become feasible, large amounts of floating-point computations will have to be executed on board at high speeds.

Aiming for accelerating the aforementioned computations, focusing on trigonometric functions and vector-matrix computations, the authors have been engaged in the development of a high-speed calculation engine for robot control and simulation application. This paper describes the structure of a calculation engine that has been realized as an LSI chip by expanding the on-board functions and making them operate at high speed and high accuracy, as well as its processing capabilities. A robot controller that makes it possible to realize active stiffness control, which has been considered inevitable in automating orbital assembly operations by remote control, is also described. Mounted with a high-speed calculation engine, this controller is capable of executing the aforementioned control and processing in a sampling time of 1 millisecond.

2. High-Speed Calculation Engine

2.1 Features of High-Speed Calculation Engine

This calculation engine is a numerical calculation LSI incorporating a digital signal processor (DSP), a device that it has become possible to mount with a floating-point calculation capability due to the greatly increased processing speeds in recent years. Using an NEC DSP, the micro PD77230, as the hardware, vector matrix functions and various elementary functions widely used in robot control and operation simulation are contained in the internal micro-instruction ROM as mask ROM. This calculation engine has the following features:

• High-performance functions, previously prepared for use in general-purpose CPUs as numerical calculation libraries, have been mounted on an LSI.

→ Has the capability to perform vector/matrix computations and statistical processings and computations.

• Ease of programming as a result of on-board functions that can be run in high-level languages.

→ Is capable of handling elementary functions (÷, √, SIN, COS, ATAN2, LOG, EXP) and various data transformation functions, and can turn DO loops into functions.

• Self-perfection as a single-chip numerical calculation accelerator LSI as a result of mounting all functions on an internal command ROM.

• Single precision floating point calculation performance of 13.4 MFLOPS (million floating operations per second).

2.2 Configuration of High-Speed Calculation Engine and Its Processing Capabilities

Figure 1 shows the configuration of our numerical calculation engine and the numerical computation acceleration module using the engine. The computation module consists of a calculation engine (DSP chip) and an external memory. By placing an application program over the external command memory and by calling various functions mounted on the calculation engine, the user describes the algorithm. Since the calculation engine is equipped with sophisticated functions, application programs can be described with ease. The exchange of data with the host computer can occur via the external data memory.

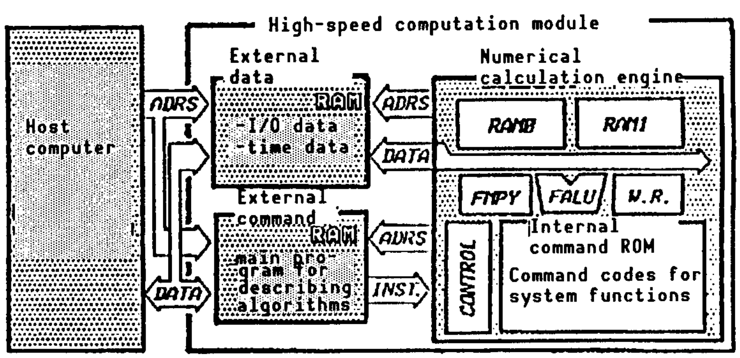

Figure 1. Numerical Computation Acceleration Module

Shown in Table 1 are the calculation engine's representative functions and their processing times. Following the performance described in the earlier report, efforts have been made to accelerate the computation operations. In the case of trigonometric functions, in particular, SIN and COS operations can be executed concurrently in 12.8 μs, while ATAN2 operations that enable solutions within the scope of $\pm\pi$ to be obtained can be executed in 15.2 μs. In the case of vector matrix functions, the inner product of a Jacobian matrix (6 x 6 matrixes) used in force control and speed resolution control and a six-element vector can be executed in 11 μs. This computation requires 36 multiplications and 30 additions, and the calculation engine has realized a practical computation performance of 6 MFLOPS.

Table 1. Calculation Engine Computation Performance

Functions for scalar variables		Function for vector/matrix variables			
÷	6.9	1x3 • 3x1	1.7	3x1 + 3x1	3.5
$\sqrt{\ }$	7.4	3x1 x 3x1	2.4	3x3 + 3x3	8.0
loge	8.4	3.3 • 3x1	2.7	3x3 • 3x3	9.9
exp	18.5	4x4 • 4x1	6.5	4x4 • 4x4	28.1
sin + cos	12.8	6x6 • 6x1	11.0	6x6 • 6x6	68.9
atan2	15.2	NxL • LxM	0.45 NLM + .75 NM + 10.5 M + 1.5		

In addition to vector/matrix computations on fixed numbers of elements, such as the three, four or six elements shown in the table, the calculation engine is capable of handling computations involving random numbers of elements, up to a maximum of 512 elements. Since the capacity of its internal data memories (RAMO, RAMI) is large, at 1,024 words (1 word = 32-bit single precision floating point format), the processing of such functions as dynamic or active stiffness control can be executed at high speed by the calculation engine alone.

3. High-Performance Robot Controller

The autonomous levels demanded of operations using a space robot can be classified into the hierarchies shown in Figure 2. Of these hierarchies, those belonging to the arm control system must be processed using much higher sampling frequencies than the frequencies required for the hierarchies belonging to the higher-level intelligent system. This requirement demands exclusive high performance control systems, but there is a limit to how much hardware a spacecraft can accommodate. Consequently, the control systems must be of a compact design. In the case of control systems for use in ground experiment equipment, they must be provided with high expansivity so that

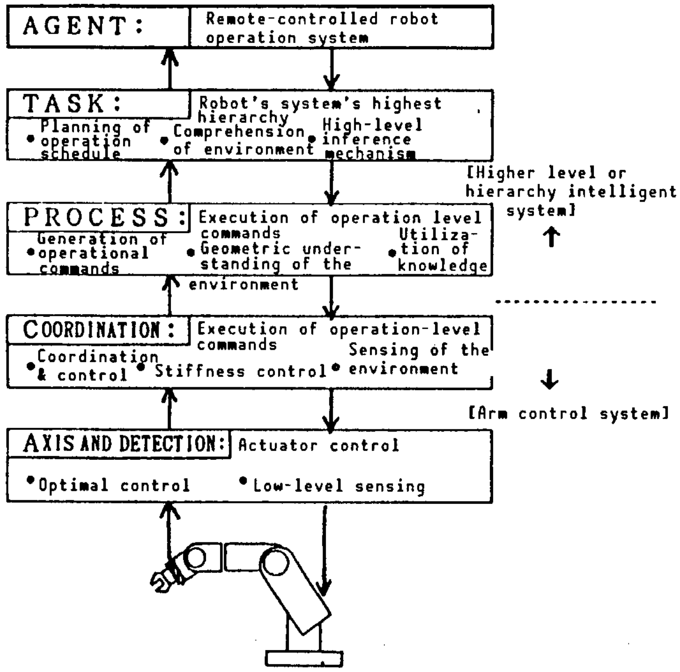

Figure 2. Autonomous Robot Control Hierarchy

they will be able to cope with the changing algorithms that vary according to the research objects.

Described below is a high-performance controller incorporating the aforementioned high-speed calculation engine which, although small in terms of hardware, has not only a high computation capability, but also a flexible expansivity.

3.1 System Configuration of Controller

Figure 3 prevents the configuration of a controller that, thanks to the incorporation of a high-speed calculation engine, features an accelerated sampling time and an increased control computation capability. The controller has the following features:

- A high sampling rate based on a high-level function control method has been realized by taking advantage of the increased computation capability of the high-speed calculation engine.

- Flexible expansivity has been achieved by separating the computation control section from the driver control section and by adopting a modular construction.

- Due to the system's open architecture, the addition of extra functions is facilitated.

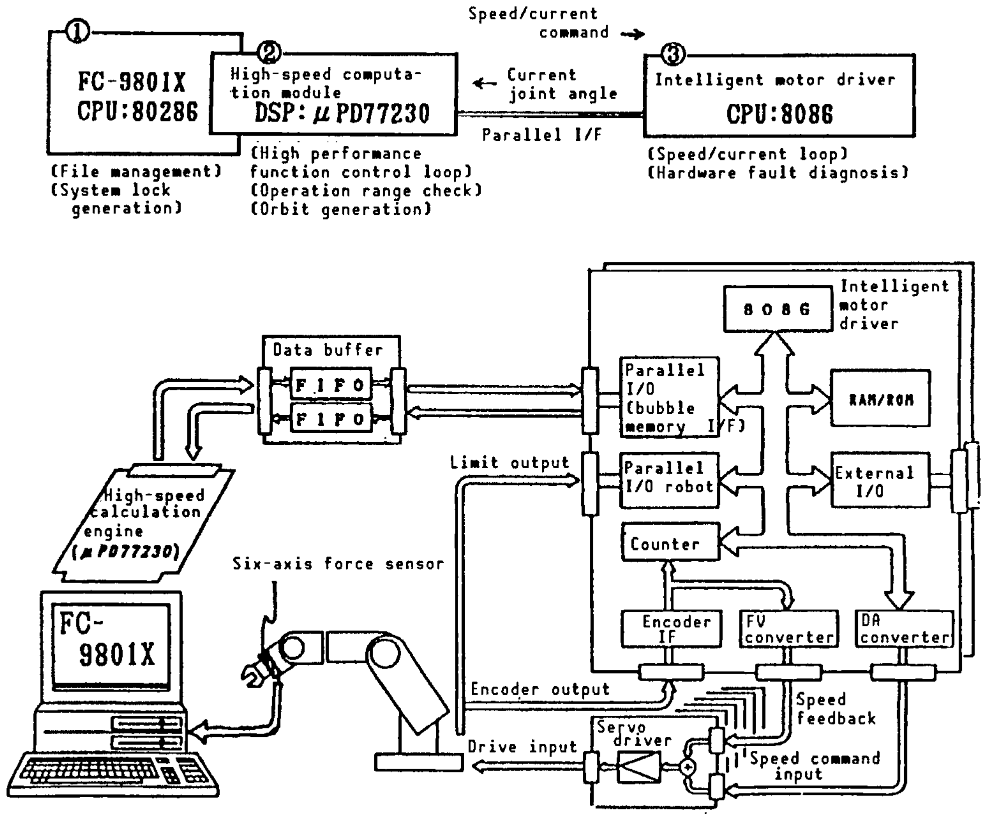

Figure 3. High-Sample-Rate Robot Controller Configuration

To realize the aforementioned features, the controller is made up of the following three sections:

1) Language processing and user interface section
   FC 9801X personal computer

2) Computation control section
   Computation module on which a high-speed calculation engine has been mounted

3) Driver control section
   An intelligent motor driver equipped with a speed/current control loop

3.2 Processing in System's Various Sections

Figure 4 shows the relationships among the controller's various sections when executing an active stiffness control using the controller. All control computations conducted at each of the sampling times are carried out in the computation control section (2), incorporating a high-speed calculation engine. The FC-9801X(1) interrupts the computation control section at intervals of 1 millisecond, making that section start a control computation.

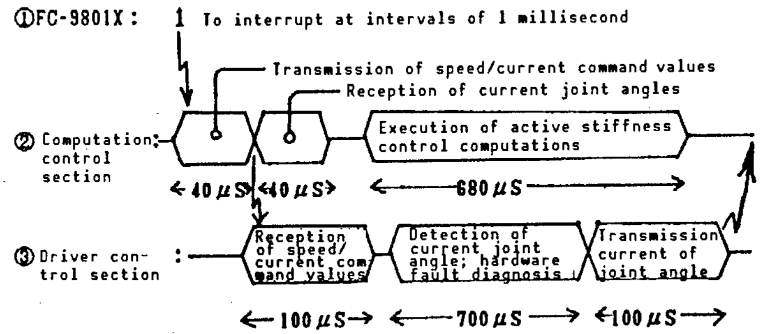

Figure 4. Task Execution Timing

At this time, the A/D conversion of the force sensor output is carried out simultaneously, and the readings from the distortion gauge obtained by the force sensor are set on the memory shared with the computation control section each time a sampling is taken. Discrete target positions and stiffness matrixes are nonsynchronously set on the aforementioned common memory.

Once activated, the computation control section immediately transmits the speed command value or the current command value calculated at the time of the preceding sampling to the driver control section (3). Due to parallel communications via a FIFO buffer, the transmission, which involves sending a command value to and receiving the current value from an arm with 6 degrees of freedom, can be executed in 100 μs. The driver control section, on the other hand, performs the following function: after receiving a current or a speed command value, it measures the current joint angles, examines the scope of operation and determines if the motor driver is functioning smoothly or not, then transmits the results back.

As described in the previous report, when using our calculation engine, the active stiffness computation can be executed in less than 700 μs, and all necessary processing, including transmission and reception, can be executed in less than 1 millisecond. Also, arming the driver control section with an intelligence capability enables the high-speed calculation engine to be liberated from the chore of I/O processing, thus making it devote itself to computation processing. This has led to the realization of a high-performance robot control method with a high sampling rate.

Shown in Photograph 2 [not reproduced] are a multiarticulated robot with 6 degrees of freedom that is driven by active stiffness control and its controller. Our controller has a driver control section for each of four axes, and control is initiated by using all six axes. Increases in the number of the control axes as the experiment progresses can be coped with by installing the driver control section and FIFO buffer parallel to the computation control section. In this case, the overall control computations are executed on the single-chip high-speed calculation engine, so high-level control computations, which are processed with interferences among axes as a precondition, can be easily realized. When the computation capacity is lacking, the computation performance can be easily increased by installing additional high-speed computation modules.

4. Conclusion

We have described a high-speed calculation engine that was developed to accelerate robot control/simulation operations, an element important for promoting the autonomous operations of space robots, and a robot controller incorporating this engine. We are now studying the controller's active stiffness control performance.

Appreciation: We hereby express our thanks to Hiromichi Fukuchi, department chief of C&C Research Laboratories, NEC Corp., for giving us a chance to conduct our current research.

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Orbital Servicing Vehicle Development Concept

43062507j Tokyo PROCEEDINGS OF THE 2ND SAIRAS in Japanese 17-18 Nov 88
pp 125-128

[Article by Tsutomu Iwata, Mitsushige Oda and Ryoichi Imai, Tsukuba Space Center, National Space Development Agency of Japan]

[Text] **0. Outline**

In recent years, along with the growth of ground robotics technology and with the increasing expectations for the full-fledged use of space by space stations and others, a heightened interest in the development of space robots has been emerging. This paper describes an orbital servicing vehicle (OSV), a representative space robot, including its concept and a scenario for its development.

1. **Why OSV Is Needed**

The space station currently under development will start operation in the latter half of the 1990s. The space station, as a semipermanent facility in space, will provide an avenue for the full-fledged utilization of space, i.e., in addition to offering a platform for conducting experiments and observations, it will furnish a base from which various orbital operations will be executed due to its being manned. Among the orbital services being contemplated for provision by the space station are the repair of malfunctioning satellites, etc., by taking advantage of the mobile service facility (MSS: being developed by Canada) and a fixed service facility which is scheduled for development during the growth stage.

The space station, however, is manned, so there are limits to its capacity to create microgravity environments ideal for the carrying out of experiments using the space environment. It is also difficult to divert the operation of the space station to the exclusive use of a specific mission. Consequently, the development of platforms as adjuncts to the space station is awaited. Platforms are large-scale satellites, and are able to receive the types of orbital services that have been unavailable to conventional satellites, such as receiving propellant supplies, exchanging equipment, etc., and they are expected to become mainstay satellites in the telecommunications, observation and experiment fields. The following types of platforms are being studied:

(1) Co-orbital platform (COP)
(2) Polar orbital platform (POP)
(3) Geostationary platform (GPF)

2. Concept of Orbital Servicing Vehicle (OSV)

For the aforementioned platforms to become operational, the precondition is that they have access to the following orbital services, in addition to a launch means.

(1) Transportation/recovery of materials (machinery, fuel, experiment materials)
(2) Exchange of machinery/modules in orbit
(3) Checks and repairs
(4) Towing

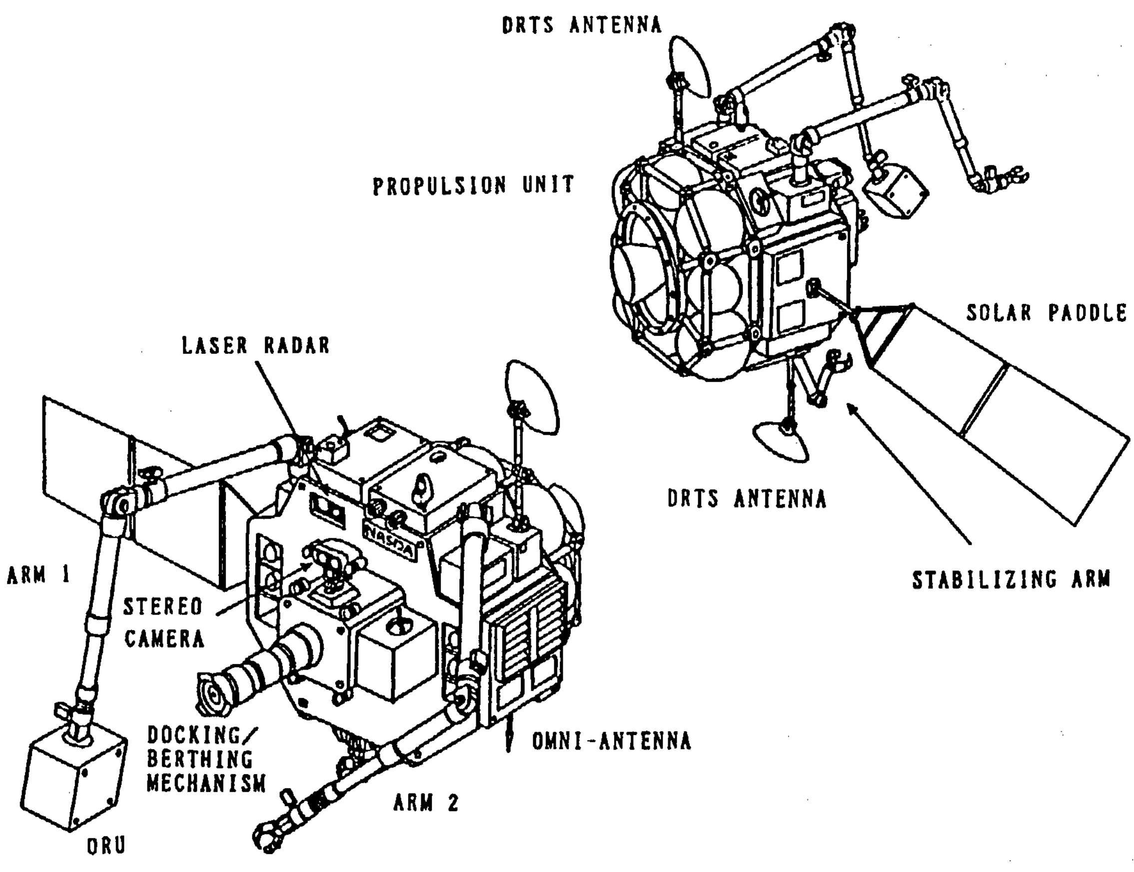

Figure 1. Configuration of the OSV

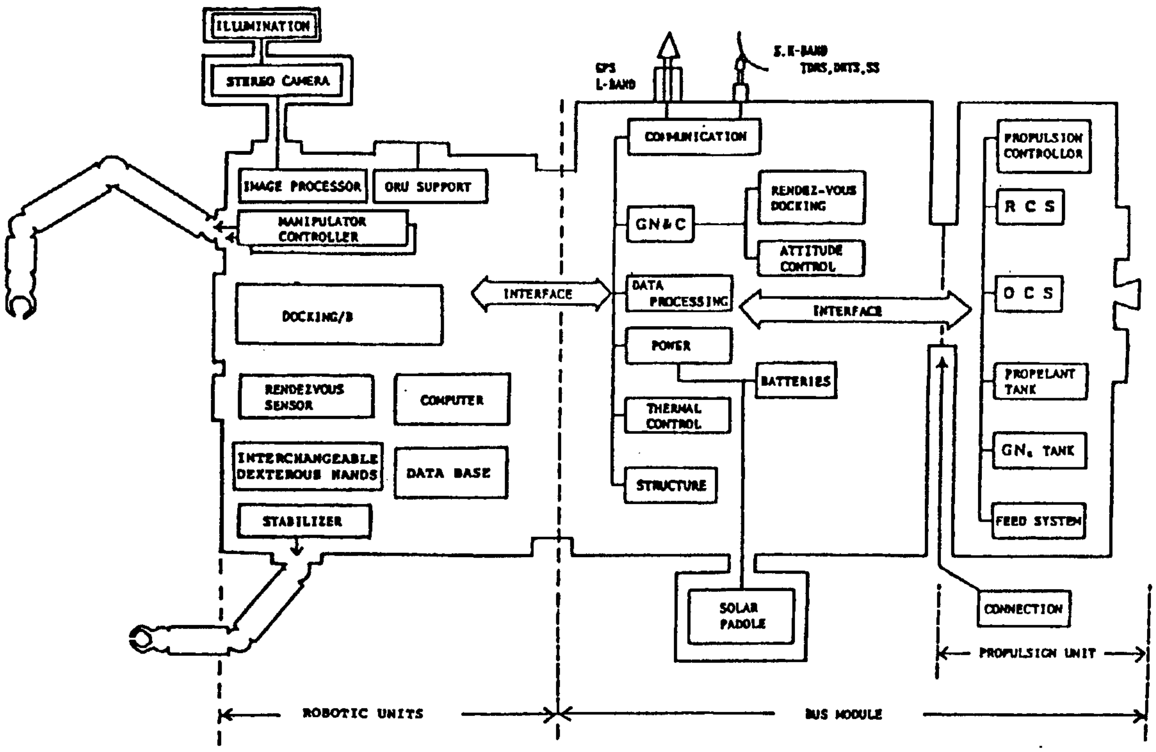

Figure 2. Block Diagrams of the OSV

OSV is designed to perform these operations and its concept is given in Figures 1 and 2. An analogue to OSV is NASA's OMV (orbital maneuvering vehicle), but this vehicle is mainly used for towing operations.

3. Technologies Needed To Develop Platforms and OSV

In order to develop the aforementioned platforms and OSV, the following technologies are needed, in addition to the conventional satellite technology.

(1) Rendezvous/docking technology

(2) Orbital servicing technology
In order to perform such operations in orbit as additions, exchanges or repairs of machinery/modules, the technology for partially autonomous robots that can be remotely controlled from either a ground station or a space station, as well as systems instrumentation technology (modular construction, ORU) that will permit the installation of systems amenable to space robot labor, are needed.

(3) Orbital propellant supply technology

(4) Large-capacity heat exhaust technology
A technique that will make it impossible to efficiently discharge large amounts of heat from mission equipment, such as an electric oven for materials experiments, into space is needed.

(5) Data processing technology
The data processing system for a platform type of spacecraft must be able to cope with the reconfiguration of the spacecraft that will result from dockings or services received in orbit, and it must also be able to process large amounts of mission data.

4. Development of STEP (Space Technology Experiment Platform)

Each of the technologies described in the preceding paragraph is new, not found in conventional satellites, yet all are needed for the platform's bus function. Consequently, before they can be applied to a practical platform, they must be tested in orbit to prove their practicality. In preparation for the development of various types of platforms, the National Space Development Agency of Japan is planning to go ahead with development of STEP, that will be used for the development of the aforementioned technologies and their demonstration testing in orbit. Since the debut of a full-fledged practical platform is expected for some time in the year 2000 or so, after taking into consideration the time necessary for the development of the pertinent technology, the launch of STEP has been scheduled for sometime around 1997.

As for the STEP missions, the platform is scheduled to undertake the following tests:

(1) Rendezvous/docking technology experiment
(2) Space robot technology experiment
(3) Two-phase fluid loop heat discharge control technology experiment
(4) Propellant supply experiment
(5) Data processing handling by an optical data bus method experiment
(6) Microgravity environment maintenance and control experiment

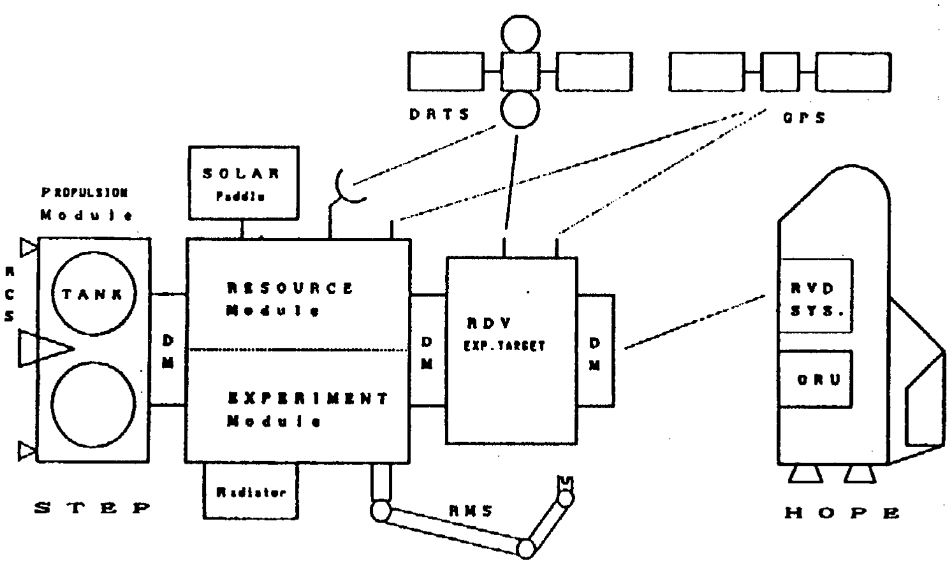

Figure 3. "STEP" In-Orbit Experiment

Figure 3 presents the concept for the operation of STEP in orbit when conducting these experiments. STEP, connected to a target vehicle (small satellite) for rendezvous and docking experiments via a docking mechanism, will be launched into an orbit of 300~500 km in altitude (HOPE co-orbit) using an H-II rocket. While serving as the target platform for rendezvous and docking experiments, the target will also be used as the target vehicle for the propellant supply experiment as well as the target of experiments (bursting, ORU exchange) conducted by the space robot.

The technologies developed during the development of STEP will be employed in the subsequent developments of the co-orbital platform (COP), polar orbital platform (JPOP) and orbital servicing vehicle (OSV). Figure 4 shows the development scenario of platform-type spacecraft.

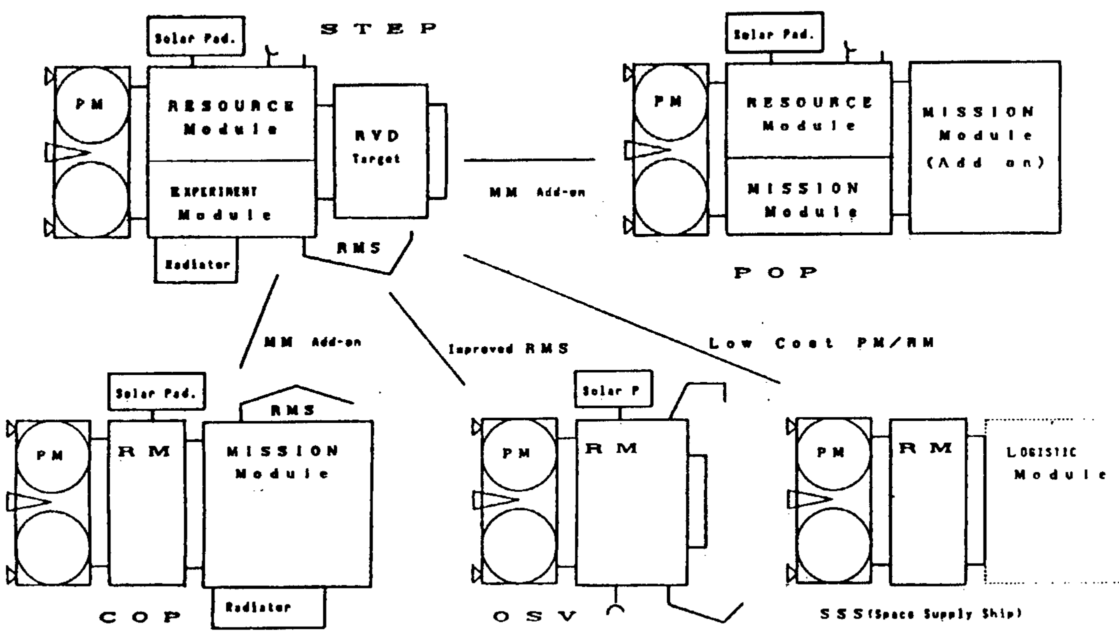

Figure 4. Development Scenario of Space Platforms

Multipurpose Experimental Modules in Space Station Proposed

43062507k Tokyo PROCEEDINGS OF THE 2ND SAIRAS in Japanese 17-18 Nov 88
pp 129-130

[Article by Tashu Sato and Hideyuki Matsumoto, JGC Corp.: "The Proposal of Multipurpose Experiment Modules in Space Station"]

[Text] 1. **Foreword**

The experimental themes scheduled to be undertaken as part of the space station program can be broadly classified into the following six categories: 1) materials experiment and manufacture; 2) life sciences; 3) scientific and engineering experiments; 4) scientific observation; 5) earth observation; and 6) telecommunication. Regarding the materials experiment and manufacture described in 1), by drawing on the idea of a high-level multipurpose plant that is now being studied on the ground, we came up with the idea for an integrated system that would be capable of performing, by itself, the entire process, from the preparation of the raw material to its synthesis to its separation and refining, and further to the disposal or recovery of the waste gas or liquid. By incorporating robots and artificial intelligence into the system, we plan to operate it by remote control from the ground. As the target for production in the materials manufacturing experiment, we selected the manufacturing of catalysts, a field that has not yet been given much thought.

Catalysts are used to control the speed of chemical reactions and are indispensable to the chemical industry. Synthesizing catalysts by taking advantage of nongravity may lead to the generation of products as sophisticated as such, the kind of which could never be obtained on the ground. In this paper, we propose a multipurpose plant-type experimental module for use in space that will be capable of synthesizing different types of catalysts for use in various applications.

2. Application to Catalyst Manufacture

Catalysts are extremely important substances for the current chemical industry, so the development of catalysts featuring high activity, high selectivity and long life will usher in new chemical processes, and their impact on the chemical industry will be very great. We believe that carrying out the task of manufacturing catalysts in the space environment by taking advantage of the nongravity found there may give rise to the generation of catalysts featuring excellent performance. Among the representative catalyst manufacturing methods are the impregnation process and the sedimentation process. In the impregnation method, a solid carrier is impregnated with an active liquid substance, and the technique is used in cases in which expensive metals, such as platinum, are used as the active substance. With the sedimentation method, on the other hand, a catalyst is produced by mixing more than two liquid raw materials and, after sedimentation occurs, the mixture is filtered, dried and sintered. Since the individual operations in these techniques have many features in common, in the experimental module we are studying, the production of various types of catalysts will become possible by merely changing the raw materials and conditions.

Here we consider a Pt-alumina catalyst, that is a reforming catalyst, as representative of the impregnation process, and zeolite as the representative catalyst of the sedimentation process. When manufacturing the Pt-alumina catalyst on the ground, water-soluble metal salts are made to be absorbed on the surface of an alumina carrier, which is then followed by filtration, cleaning, drying and sintering. As a result, it is difficult to obtain a uniform distribution of the microscopic metal particles due to the effects of gravity. In a nongravity state, it is assumed that the metal particles will be uniformly retained over the surface of the alumina carrier, thus possibly enabling a catalyst of higher activity and selectivity to be manufactured. Again, although zeolite is hydrothermally synthesized under pressure, it is not subject to the effects of gravity, so zeolite having much larger crystals can be synthesized. The possibility exists of manufacturing a film-like zeolite, an accomplishment that has yet to be realized on the ground.

3. Process Flow

As shown in Figure 1, the flow of the catalyst synthesis process is made up of: 1) the preparation of raw materials; 2) the mixing of the raw materials, 3) reactions; 4) infiltration; 5) cleaning; 6) drying; and 7) burning. The synthesis process, however, varies somewhat depending on the catalyst being made. Furthermore, the infiltration and cleaning processes demand recovery of the waste liquid, while in the drying and burning processes the waste gas needs to be discarded. Since the major component of these waste products is water, it becomes necessary to develop a water cycle system. The systems used in these processes must be as compact as possible, and those systems that can withstand repeated use will be used again and again, minimizing the number of such systems. As conceived by us, the equipment will not use pipes to connect its component systems, so changing the order of system connections will be implemented by changing their positions using a robot remote controlled from the ground. The maneuvering of the individual systems will be automated, and their operation will also be automated by artificial intelligence. The use of this equipment will make it possible to synthesize various types of catalysts by altering the reparation of raw materials, the combination of the component systems according to the operating conditions, and the operating conditions themselves. A conceivable mode of the

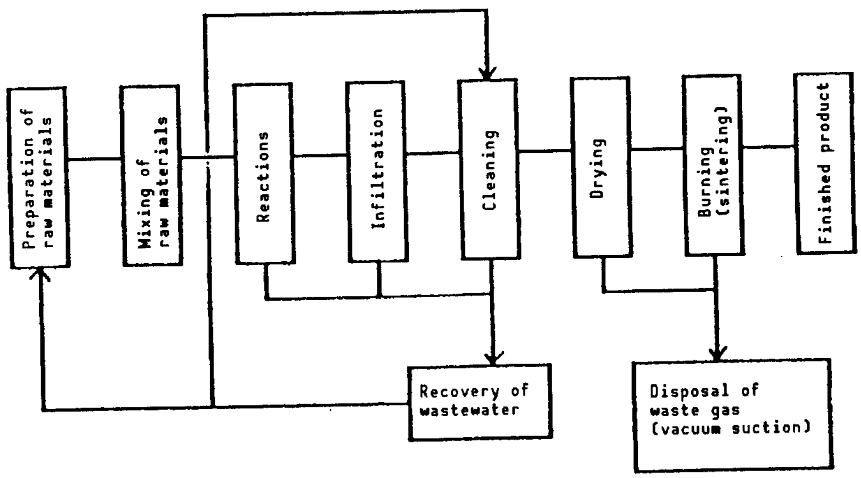

Figure 1. Flowchart of Catalyst Synthesis

equipment's operation involves lifting the necessary materials from the ground, synthesizing a catalyst, and recovering the finished products.

4. Conclusion

The space experimental module described in this paper is designed for synthesizing catalysts, but its concept is applicable to the synthesis of other materials and to organic synthesis applications. A multipurpose experimental system in space would enable various types of experiments to be planned.

Space Robotics, Automation Research Forum Report

430625071 Tokyo PROCEEDINGS OF THE 2ND SAIRAS in Japanese 17-18 Nov 88
pp 159-161

[Article by Yoji Umetani, Tokyo Institute of Technology]

[Excerpts] **1. Foreword**

The successful resumption by the United States of its space shuttle program at the end of September this year is expected to give not a small impetus to Japanese efforts toward space development. With it, the R&D of space robots will be accelerated to a great extent.

This paper represents an interim report on the activity of the "Space Robot Automation Survey and Research," a project undertaken in 1987 by the Space Environment Utilization Promotion Center at the request of the National Space Development Agency of Japan. The survey and research in question has been carried out by an organization called the "Research Forum" (generally referred to as the Space Robot Forum), and following the survey and research during the initial year of the program (FY 1987), this fiscal year the survey and research is to be pursued by two working groups. [Passage omitted]

3. Developing Thoughts on Technical Tasks

In this paper, the technical tasks of robots operating in the space environment are examined.

Let us first consider the scenario in which a space structure is built in orbit and operated by a space robot, and then proceed by examining the elementary technologies that will be necessary for this to become a reality.

The development of the concepts in this section will provide the basis for the proposition in the next section. As designed by us, the space structure construction and operation will follow this scenario.

The constituent elements discussed in this paper are the basic module (a module forming the core of the space structure which performs the basic functions), a structural module, mission equipment and future modules, and a space robot.

(1) The first stage involves the launching of the basic module and space robot into orbit. The basic module is provided with the basic equipment necessary for the operation of the space robot, i.e., the communications system, electric power system, attitude control system and a propellant storage tank. The space robot is usually anchored to the basic module's docking board and receives electric power and propellant supplies.

(2) During the second stage, the structural model is assembled. A rocket lifts the structural module into orbit close to the basic module. The space robot meets the structural module, makes a soft docking with it by using its manipulator, and tows it to the basic module for attachment.

The structural module contains a foldable structure in its bay, and this foldable structure is unfolded with the help of the space robot. Since the space robot is expected to assist in the unfolding, the foldable structure can have a simple mechanism, and the space robot also provides a guarantee against unexpected emergencies, such as the failure to unfold.

(3) The next stage involves the installation of mission systems, such as solar reflectors, large antennas, and space experiment laboratories, that have been put into the orbit in succession.

As was the case with the structural module, these systems are towed by the space robot to where they are to be installed on the structural module, and are unfolded and assembled with the space robot's aid.

According to another scenario, multiple space robots will cooperate in assisting with the docking, attachment or coupling operations, and allowing the space robots to assume the bulk of the responsibility for making a soft docking would eliminate the need to provide the payloads with extra docking gear.

(4) During the growth stage, a manned module for a short human stay, for example, can be attached. A facility where several astronauts can stay for a short period, the module will first be launched into orbit, unmanned for coupling to the structural module, and the astronauts will board it after a space robot has checked its capabilities and confirmed its safety.

(5) During the future stage, scientists may be able to use such a manned module to carry out necessary space experiments, and engineers may be able to haul a malfunctioning satellite into the pressure chamber of the manned module for on-site repairs.

During such an operation, the space robot will be fully employed supplying the necessary materials, recovering the finished products, towing a malfunctioning satellite, or returning the repaired satellite to orbit.

4. Propositions

The research and development of a robot generally begins with clearly defining the stages of and plans for its activity.

The next step in R&D is to extract the technical features of the robot, which can be obtained by unraveling the plot of the unfolding scenario, while the final stage involves analyzing those features, polymerizing them, and crystallizing them into technical tasks.

Next, in order to realize a space robot whose technical tasks have been so crystallized, a project worthy of the feat will have to be devised. The project itself will have to be able to contribute to Japan's space development, but what is being sought the most here is to make sure that the project's technical tasks are in the same orbit as those exemplified earlier. In other words, the execution of the project will immediately lead to solutions of the technical tasks.

The Research Forum solicited the opinions of its members through a questionnaire and obtained several concrete concepts for space robots. We examined several representative concepts to see if they could be worthy of the project requirements mentioned above. The outcome of the study is the three projects listed below, which we have termed "propositions" as a reflection of our desire to see their realization.

(1) To Construct Space Structures in Orbit Using Robots

A space robot will be developed that will be used to build structures comprising an infrastructure focused on an unmanned mission module (a completely automated and robotized space experiment module, for example) in a low orbit.

These foldable structures will be equipped with systems and instruments that can be entirely assembled by a robot, and the existing H-II rocket will be used for their transportation. The essential requirements for the space robot to be developed are that it has two arms, that multiple robot units be capable of cooperating during an operation, and that it be provided with intelligent and autonomous functions. The possibility is high that the robot will be of a master-slave type, with commands coming from the ground by remote control.

(2) To Develop an Experimental Space Module (COSMO-LAB)

A large variety of automated laboratory units will be combined inside the main body of the experimental space module. Placed inside the module will be a laboratory automation robot (LA robot) to perform such operations as the transfer of test samples and their attachment to and detachment from the units, the distribution of supplementary materials to the units, and treatment before and after experiments. Inside the module, the controlled distribution of gases, fluids, electric power utilities and signal lines to the various units will occur, and data processing equipment to perform such operations as planning and experiment scheduling, and determining the experimental procedures, as well as the processing, transmission and storage of the experimental data, will be installed.

This experimental space module will liberate the researchers from the constraints associated with the "Single-Process, Single-Operation"-type experiments currently being planned, enabling them to conduct complex, multistep experiments.

(3) To Systematically Develop the Ground Testing Facilities That Will Be Used for Performance Evaluation and Verification of Space Robots

It is impossible to simulate on the ground a perfect space environment, especially a microgravity environment. In the development of a space robot, however, it is indispensable that the robot undergo demonstration tests to evaluate and confirm its performance. Consequently, a complete system of testing facilities must be established on the ground.

To that end, space environment simulation and testing equipment for space robots, as well as testing and performance evaluation methods, must be systematically implemented.

In order to simulate the space environment in which a space robot can be tested, various methods are available, such as software simulation, an air table, an underwater simulator, and a hybrid simulator, and a standardized master-slave system is also required to test the remote control capabilities. These systems must be used selectively, depending on the test objectives.

Space Structure Construction by Robots Reported

43062507m Tokyo PROCEEDINGS OF THE 2ND SAIRAS in Japanese 17-18 Nov 88
pp 162-167

[Article by Hironori Fujii, chairman, Working Group No 1, Research Forum on Space Robotics and Automation, and professor, Tokyo Metropolitan Institute of Technology: "On Construction of Space Structures Employing Robot Technology--Report of Working Group No 1 for Research Forum on Space Robotics and Automation"]

[Text] 1. **Foreword**

Two working groups have been established within the Space Robotics Forum since May 1988, with Working Group No 1 having been assigned the research job entitled "Studies on Autonomous Assembly Robots in Low Orbit." A total of 29 experts in the two engineering fields or robotics and space have voluntarily participated in our working group, and they are now grappling with the theme. In this interim report, the author intends to describe the contents of the studies undertaken so far, as well as the achievements that we intend to realize within the year.

One measure of our working group's activity policy is its adherence to the basic policies put forth in the FY 1987 "Report on Achievements," i.e., 1) unmanned operation is the starting principle; 2) the operation will be robotized; and 3) the safety of humans is the first priority.

As part of the preconditions for its activity, the activity policy for Working Group No 1 says, "The means of transportation to low orbit, the reentry technology and the ground support facilities will be contemplated on the basis of NASDA surveys and prospects," and "The goal is to come up with proposal-type achievements that ultimately will take concrete shapes in the form of projects deemed essential, their execution plans and their budgets."

2. Tasks Requiring Study

Before committing ourselves to the research theme "Studies on Autonomous Assembly Robots in Low Orbit," we, the members of Working Group No 1, discussed what tasks currently demand study. The results are given in Table 1.

Table 1. Tasks Requiring Study

I. Task Analysis

1. Operation analysis in line with scenario (task analysis)

2. Assembly task analysis--Characteristics of object to be worked on
   Manipulation function
   Work environment
   Analysis of operation procedures

3. Setting of an envisioned mission (requirements
   Setting of multiple requirements, such as timing and scale

4. Specifications and design concepts of the target platform (must at least conform to robot assembly)

5. Concepts of the structures to be assembled

6. Configuration of the experimental space module and its assembly in space

7. Prior survey for setting of prospective missions

8. Handling of structural materials

II. Constraint Conditions and Environment

1. Clarification of constraints

2. Conditions of the target structure

3. Shape of the structure suited for assembly by an autonomous assembly robot

4. Coping with the impact from external sources, such as solar light and collision with meteorites

5. Resource preconditions

III. Functions and Roles of Robots

1. Task analysis → clarification of roles of robots

2. Work strategy

3. Formulation of a scenario for assembly

4. Defining robotization, and defining the structures to be assembled

5. Analysis of robot functions

[continued]

[Continuation of Table 1]

[Continuation of III. Functions and Roles of Robots]

6. Analysis of functions of assembly operations under a nongravity state

7. Setting of robot functions

8. Tabulating robot functions

9. Without taking into consideration how robots will execute their jobs or what their autonomous capabilities will be, the development of robots will be undertaken in stages, aiming at their ultimate acquisition of autonomous capabilities.

10. Dismantling of robot functions--a) two arms; b) redundant degrees of of freedom; c) flexible arms; d) mobile capabilities; e) sensors

11. Study of the kinds and numbers of required robots based on the analysis of the operations to be undertaken

12. Analysis of robot motions based on findings obtained during the analysis of the operations to be undertaken

13. Extraction of technical tasks requiring solutions for realizing autonomous controls

14. Autonomous levels

15. Design of an intelligent robot with visual and judgment capabilities

16. How to use various types of sensors

17. Exploring supportive and peripheral systems for assembly robots

18. Setting of functions required of space robots and the entire system, and their specifications

19. Studies on dispersed control/central control systems (burden-sharing among robots, basic modules and the ground)

20. Control of space robots with a manipulator (space-traveling-type) (recoilless operation, two arms, optimal bus, etc.)

21. Operating methods

22. Autonomous operation scheduling prior to the start of the operation based on results of the recognition of the environment, and confirmation of the schedule using simulations

[continued]

[Continuation of Table 1]

[Continuation of III. Functions and Roles of Robots]

23. Recognition and study of emergency situations using artificial intelligence

24. Fault diagnosis and repairing malfunctions

25. Joint operation programs using multiple robots and their controls

IV. Fundamental Technologies and Specifications

1. General

1) Originality of the technology
2) Prediction of advances in related technologies
3) Extraction of fundamental technologies, proposals for their R&D, and an analysis of their target specifications
4) Grasping of routine images (the size and weight of a module, the distance the module needs to be towed, and the size and weight of a robot)
5) Procurement of artificial intelligence elements and studies involving how to use them

2. Teleoperation

1) Teleoperations
   Teleoperation
   Intelligent teleoperation (partially autonomous operation)
   Interface to autonomous operation
2) Design of robot control systems
   Teleoperation
   Autonomous control
   Sensor feedback
3) Tele-existence technology

3. Communications and information

1) Information display technology
2) Methods of effecting communications between robots and humans as to the progress of work and the results of the recognition of the environment
3) Media technology--What kinds of media are needed?
4) Communications among robots so that they can work cooperatively and be controlled

[continued]

[Continuation of Table 1]

[Continuation of IV. Fundamental Technologies and Specifications]

4. Sensors and recognition

1) Sensor fusion for assembly operation
2) Recognition for traveling objects
3) Three-dimensional visual sensors
4) In order to realize force and attitude controls between the object and robot in a nongravity state, recognition of the environment by the robot and sensors (preparation of maps)

5. Controls

1) Force and attitude controls for the robot and object in a nongravity state
2) Controls of robot's spatial movement program and movements
3) Space manipulator's movement and force controls, and control of synergetic motions of both arms
4) Control of the attitude of the platform during an operation

6. Mechanisms

1) Movement manipulation--mechanism
control
sensing (including sensor data analysis)
2) Of the various types of actuators, what type of actuator is most suited to use in space robots? Or, is it better to develop a new actuator?
3) End effector
4) Actuator gear system
5) Multifunctional hands and exclusive-use tools

7. Rendezvous/docking

1) High-precision technology to bring two bodies together at a rendezvous (position sensor, navigation and station-keeping technologies)
2) Soft docking technology (including the technology enabling the robot to contain structural vibrations)

8. Interfaces

1) Operation interface
2) Human interface--How to systematize the whole

[continued]

[Continuation of Table 1]

V. Synthesis of Robots, Proposal for Robot Models and Their Evaluation

1. Synthesis of robots
2. Proposal for robot systems
3. Entire system construction method
4. Evaluation of the system concept
5. Comparison of cost and efficiency with human operation
6. Design of OMV with intelligent robot on board
7. Maintenance robot (including energy supply)
8. Robot to assist structures with unfolding (work-sharing between the unfolding structure and robot)

VI. Development Program

1. Objective and goals
2. Proposal for development concepts
3. Full-dress research meeting and the scope of the project (narrowing down the scope of development of required technologies)
4. Drafting of a development program
5. Studies of possibilities and limits of ground tests, as well as of ground simulation experiment facilities
6. Estimates of development cost
7. Sorting of problem (tasks)
8. Solutions to technical problems and their directions

VII. Others

1. Survey of literature

These tasks have been broadly classified into seven categories. As for the task analysis contained in Category 1, the results of our studies are given below. The constraint conditions in Category 2 have been studied by members of NASDA. Based on the results of these studies, the tasks contained in the other categories are being investigated by members of our working group, and some of the findings are described below. The ground experiment facilities in Category 6 comprise one of the most important study items, and studies are being conducted on them.

3. Analysis of Tasks

Task analyses of the infrastructure that will be used to conduct various space experiments were generated by taking advantage of the specific features of the space environment (COSMO-LAB) with respect to its assembly in low orbit (Target A) and to its maintenance, checkups and repairs (Target B). These are listed in Table 2 (because of space constraints, some have been omitted). As for the timing of the task analyses, although no actual structure was presented, the work was conducted by taking into account every possibility. Based on the results of these analyses, studies will be made of the drafting of concrete basic plans, the setting of the assembly sequence, and the fundamental technologies and synthesis described below.

Table 2. Task Analyses

Target A: To Assemble COSMO-LAB in Low Orbit

I. To Recover Materials Lifted Into Space

(A) Rendezvous with the material

A1 Transferring

1. Confirm the material's status and check its functioning
2. Confirm the information on the material's orbit
3. Determine the position for docking operations
4. Prepare a rendezvous flight plan
5. Separation and launch from the basic module
6. Approaching the target material

A2 Recognition

1. Recognition of the environment
2. Probe, discovery and identification of the material
3. Recognition of the status of the material (presence of abnormality)
4. Measuring the relative distance, motion and attitude
5. Probing for portion where connection can be made

(B) Docking with the material

B1 Hard docking

1. Approaching the material
2. Controlling the relative position and attitude
3. Docking motion

[continued]

[Continuation of Table 2]

[Continuation of B1 Hard docking]

4. Shock control (vibration mitigation, absorption and attenuation)
5. Treatment after docking has been made

B2 Soft docking (omitted)

(C) Transportation of materials

C1 Transferring

1. Recognition of the object
2. Grasping the material
3. Determine where to move the material and plan for an orbit
4. Issue a command to move
5. Transfer and attitude controls
6. Collision avoidance
7. Position confirmation

C2 Recognition

1. Modeling
2. Recognition of the environment
3. Identification and extraction of the target
4. Recognition of one's own position and attitude
5. Recognition of the relative position and attitude
6. Means

(D) Anchoring of materials

D1 Docking

1. Recognition necessary for docking
2. Position and attitude controls
3. Execution of docking
4. Check the coupling for confirmation

D2 Installing

1. Detect the material's direction and attitude
2. Have control of the material for corrections (orbit, position, attitude, and relative stoppage)
3. Make preparations for a contact
4. Installation
5. Extracting materials
6. Post-treatment

[continued]

[Continuation of Table 2]

D3 Retention (keeping in position)

1. Recognition necessary for retention
2. Retaining gears
3. Maintenance and control of the retention

<u>II. Assembly and Unfolding</u>

(E) Assembling

E1 Noncooperative components + robots

⇔ Noncooperative components + robots

1. Work planning

↓

2. Significant transfer of robot A	2'. Significant transfer of robot B
3. Robot A approaches component A	3'. Robot B approaches component B
4. Recognition and identification	4'. Recognition and identification
5. Measurements (position, attitude)	5'. Measurements (position, attitude)
6. Position and attitude corrections	6'. Position and attitude corrections
7. Hold component A	7'. Hold component B

↓

8. Communications between robots
9. Robot A approaches robot B
10. Robot to robot docking
11. Confirmation and measurement of the installation position
12. Installation, latching and tool manipulations
13. Confirmation of the operation just concluded
14. Dispersion

E2 Cooperative components ⇔ noncooperative components + robots (omitted)

E3 Large components ⇔ small-size components + robots (omitted)

(F) Fitting out

F1 Blanket coverage

1. Measurement, recognition and identification
2. Work planning
3. Execution of the work
4. Completion of the work

[continued]

[Continuation of Table 2]

(G) Unfolding

G1 Active unfolding

1. Examine if it is opportune to start unfolding or not
2. Monitor for collisions
3. Release the latches
4. Give order to start unfolding
5. Monitor the unfolding operation and make fault diagnosis
6. Assist in or give support to failures involving unfolding motions
7. Control vibration and attitude after the unfolding operation is completed (on the side of COSMO-LAB itself)
8. Confirm completion of unfolding operation

G2 Passive unfolding (omitted)

(H) Post-treatment

1. Detect and recognize any tools or waste products remaining
2. Retrieve and hold those tools or waste products
3. Determine how to dispose of those tools or waste products
4. Encase, eliminate and discharge those tools or wastes
5. Surface cleaning

III. Confirmation of Functions

(1) Confirmation of functions (items to be confirmed)

1. Confirm the results of the assembly (external appearance inspections, confirmation of the shape)
2. Test movable parts
3. Inspect for leaks (confirmation of airtightness)
4. Confirm strength (torque checks, etc.)
5. Vibration tests (identification of dynamic characteristics, etc.)
6. Thermal characteristic checks
7. Confirm electric systems (disconnections, shorting, single input/output
8. Confirm mission/bus equipment (antennas, solar cells, etc.) performance

[continued]

[Continuation of Table 2]

Target B. To Operate, Maintain, Inspect and Repair COSMO-LAB in Low Orbit

IV. Operation, Maintenance, Inspection and Repair

(J) Operation, Maintenance, Inspection and Repair

J1 Operation

1. Rendezvous and docking with the transport vehicle
2. Loading of supplies (samples, fuel, replacement equipment)
3. Ferrying and loading of supplies aboard COSMO-LAB
4. Ferrying of finished products from COSMO-LAB to transport vehicle and subsequent loading

J2 Inspection

1. Routine fly around COSMO-LAB (fly-around)
2. Visual inspection of the external surface (deformation, peeling, perforation, deterioration)
3. Inspections for leakage and loose screws
4. Abnormality detection, fault identification and diagnosis

J3 Maintenance and repairs

1. Repair planning based on the repair data base (studies of the methods and programs, and their tabulation)
2. Selection and exchange of tools
3. Recognition of repair sites
4. Transfer to the repair site
5. Removal of obstacles
6. Exchange of malfunctioning components, and ORU
7. Exchange of structural materials and other jobs accompanying the operation, such as mounting and tightening of hooks, screws and bolts, their removal, position aligning, welding and reinforcing
8. Unfolding of structures
9. Installation of connectors, etc.
10. Coating
11. Cleaning
12. Recovery of scattered objects

J4 Others

1. Towing COSMO-LAB and changing its attitude (for large-scale repairs by moving it to SS)

[continued]

[Continuation of Table 2]

V. Recovery and Storage of Foldable Structures

(K) Recovery and storage of foldable structures

K1 Active storage

1. Guide the robot to where the work is to be conducted
2. Remove accessories
3. Checkout prior to recovery and storage (safety confirmation, fault diagnosis, checks for alien materials)
4. Release or disengage the latch
5. Give command to start the storage operation
6. Reduce the size of the folded structure (position, attitude and vibration controls accompanying the transfer of the center of mass)
7. Assist the robot in case of problems
8. Checkout upon storage completion
9. Pulling out (disengagement)
10. Retention and transportation
11. Recovery and storage

K2 Passive storage

1. Guide the robot to where the work is to be conducted
2. Remove accessories
3. Interlocking to LAB
4. Checkout prior to storage
5. Release or disengage the latch
6. Folding and storage by the manipulator
7. Checkout upon storage completion
8. Pulling out (disengagement)
9. Retention and transportation
10. Recovery and storage

4. Basic Plans

As the first-stage implementation of concrete programs, the basic plans given in Table 3 have been drafted. Parts of the COSMO-LAB concept relating to space experiments have been brought together under the category of mission systems, with the details to be worked out by Working Group No 2. As for the robot system, two types of robots are being considered: one is a fixed type of robot that stays fixed to the scaffold (Scaffold), with the other a mobile type robot that moves freely on the scaffold (Free Flying). As for their shape, functions and numbers, concrete studies are about to begin in connection with the assembly sequence described below. As shown in the table, the resources system is made up of various bus sections. Of them, the control system not only controls the assembly and operation, but also plays the role of centrally directing the higher level control of the mission

Table 3. Basic Plans

1) Mission system	Pressurization experiment section
	Exposure experiment section
2) Robot system	Free-flying robot (Free Flying)
	Scaffold robot (Scaffold)
3) Resources system	Control system
	Electric power system
	Thermal control system
	Communications system
	Orbit, attitude and vibration controls
	Fuel system
	Storage system
	Water and gas restoration systems
4) Space foundation system	Main ring
	Docking port

system. The space foundation system is configured to maintain the integration of all these systems and functions, and a ring-shaped space foundation system is currently being studied as a formation that will enable it to position itself near the center of mass of the entire structure, thus ensuring an environment of microgravity in the mission system.

5. Assembly Sequence

In Table 4 is a draft for the assembly sequence, prepared based on the aforementioned basic plans. The assembly sequence will be subject to further refining pending in-depth analyses of the tasks.

6. Development Plans

We studied the preconditions described above and the prospects for the various experimental space programs, such as SFU, (H-II launch), STEP, JEM and COP, and held sessions to ensure coordination with Working Group No 2. The results comprise the development plans shown in Figure 1.

Table 4. Assembly Sequence

1.	Launch of Free Flying robot
2.	Launch of scaffolding, temporary power system and resources system materials, and Scaffold robots
3.	Unfolding of the temporary power system, and anchoring of materials
4.	Unfolding of the scaffolding and of the resources system
5.	Launch of mission modules
6.	Towing of mission modules and assembling them, followed by piping and wiring work, etc.

7. Questions Exchanged Between Working Group Nos 1 and 2 and Results of Coordination

The two working groups established this year are expected "to work cooperatively and to tackle tasks that are compatible with one another." To that end, we held open discussions. Table 5 presents questions aired during the discussions.

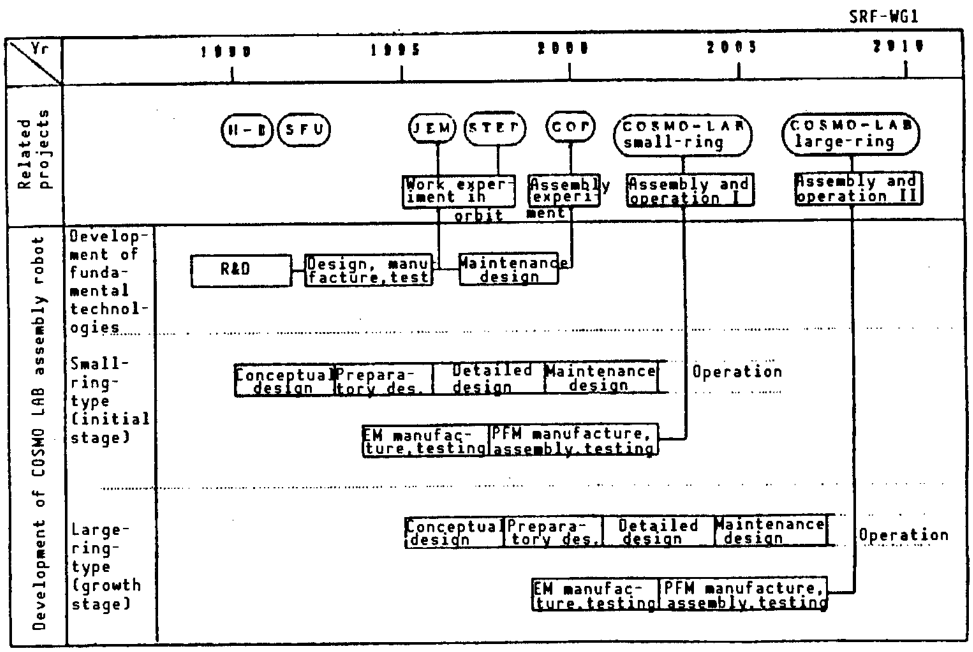

Figure 1. Draft Schedule for COSMO-LAB Assembly Robot Development

Table 5. Questions Between Working Group Nos 1 and 2 and Consensus Results

1. Questions from Working Group No 1 to Working Group No 2

   a. What is the experiment and operation profile for the experimental module?
   b. What are the demands for external support (including maintenance)?
   c. What are the procedures for handling dangerous objects during the experiment?

2. Questions from Working Group No 2 to Working Group No 1

   a. What is the concept of COSMO-LAB as a whole?
   b. What are the scenarios for COSMO-LAB assembly?
   c. How are COSMO-LAB repairs in orbit envisioned?

3. Items Coordinated

   a. Interfaces between experiment module and external robots
   b. Size of the experimental module and how to assemble it
   c. Scenarios for supply and recovery
   d. Development schedule

8. Conclusion

This paper represents an interim report on the activity of Working Group No 1 established in May of this year within the "Research Forum on Space Robotics and Automation." We, the members of this working group, plan to go ahead with studies involving much more concrete execution plans.

Unmanned Space Experiment Module (COSMO LAB) Concept Reported

43062507n Tokyo PROCEEDINGS OF THE 2ND SAIRAS in Japanese 17-18 Nov 88 pp 168-173

[Article by Kotaro Matsumoto, National Aerospace Laboratory: "The Concept of Unmanned Space Experimental Module (COSMO LAB)--Interim Report From Working Group No 2 of Research Forum on Space Robotics and Automation"]

[Text] 1. **Foreword**

With the launch of the space station scheduled for 1996, the demand for space environment utilization will increase further. However gigantic the space station may be, its resources are still finite, and the extremely expensive astronaut-worker resources, in particular, are known to be in short supply for meeting even the current demand. It is thought that the presence of human beings in orbit is needed in a space experiment because humans have high-level recognition and judgment capabilities, as well as flexibility. However, it cannot be denied that the presence of human beings places large constraints on the contents of an experiment.

From the former viewpoint, therefore, at ARC, NASA, studies are being made of automation focusing on the rearing and culture of animals and plants for life science experiments. Regarding the latter, GE is studying, under contract from NASA, the feasibility of manufacturing GaAs crystals and VLSI based on GaAs in an unmanned space experiment system.

The realization of such unmanned experiment systems would greatly mitigate the constraints placed on experiments due to the fact that the space station is a manned system, and the demand for experiments would increase greatly, thus making the space station business economically viable. Furthermore, separating manned systems from unmanned ones would heighten the efficiency and safety of the space environment utilization system as a whole.

From the foregoing viewpoints, with the era of the full-fledged utilization of the space environment at hand, the author believes that promoting the development of a space experiment system that will be highly autonomous due to the incorporation of automation technology can be considered highly pertinent and meaningful. In my opinion, Japan is being called upon to aggressively put to good use its world-leading potential in the field of industrial robots in order to develop an unmanned space experiment system ahead of the rest of the world.

2. How To Proceed With Studies

Working Group No 2 is promoting studies on space experiment robots on the procedures listed below.

(1) Setting of timing for realization: The most effective, yet economically feasible, timing for the realization of the project will be set after taking into account the expected increase in the demand for space environment utilization and the project's consistency with existing space development programs.

(2) Establishing the image of COSMO LAB: For the benefit of the following discussions, an outline of the COSMO LAB will be obtained after considering the likely mode of its utilization at the time of realization predicted in 1) and the technological advances involving the robots to be used in the experiments. Included in this process are discussions on the basic characteristics of COSMO LAB, an outline of its composition and the philosophy of its system configuration.

(3) Task analysis: Based on the First Material Processing Test (FMPT) and the mission data sheets for the space station, the space experiment process will be sorted out and classified into common work units, and tasks specific to each of the utilization fields (materials, life sciences, etc.) will be listed.

(4) Selection of task execution form: Decisions will be made involving how to execute each of the tasks. Table 1 gives the forms of task execution currently under consideration.

Table 1. Forms of Task Execution in COSMO LAB

1. Tasks will be executed by the COSMO LAB's central control system.
2. Tasks will be executed by robots.
3. The jobs involved in task execution will be handled by automated systems.
4. Preparations will be made in advance on the ground.
5. Tasks will be executed through manned space activities.
6. Tasks will be executed by remote control from the ground.
7. Certain tasks will not be undertaken.

(5) Extracting the technical tasks necessary for robotization: Regarding the tasks to be undertaken by robots, details of their execution, and constituent elements will be used to extract the technical tasks.

(6) Establishing the image of COSMO LAB as a robot: Based on the results of (4) and (5), a concrete image of the COSMO LAB and robot work will be established.

Based on the results of the studies mentioned above, technical elements that need to be developed will be identified, and development plans will be drawn. As of this writing, studies of (1) through (4) are nearly complete.

3. Unmanned Space Experiment Robot System--COSMO LAB--and Its Outline

3.1 When Will It Be Realized?

The preconditions for the development of COSMO LAB are that the results of ongoing developments, such as the experiment module for the space station program (JEM) and other space development plans related to the utilization of the space environment such as FMPT, be fully exploited and that the domestically-developed H-II rocket be used as the launch rocket.

The development of COSMO LAB will go through the three stages of technical development, demonstration of the technology, and development, and the realization of COSMO LAB in its final operation phase will be achieved around the year 2003.

3.2 Mission of COSMO LAB

The COSMO LAB is basically characterized as a "multipurpose space experiment laboratory" that will be performing such operations as trial manufacturing testpieces destined for commercial production on the ground and preparing for future large-scale activities in space. We consider the image of COSMO LAB as a space factory designed to manufacture large quantities of specific materials in the space environment to be slightly premature.

By taking advantage of the characteristics of the space environment, such as the high vacuum of the micro G level, the "multipurpose space experiment laboratory" will be used to conduct unmanned basic research and experiments involving the trial manufacture of testpieces, mainly in materials and life sciences fields, under a microgravity environment that lasts longer than and is of a superior quality to that available in the space station.

COSMO LAB will take upon itself part of the burden of leading-edge research on the ground. To that end, it will be incorporating as much of the automation technology, robotics technology and tele-science technology as possible, and the projected design capabilities of the space lab are that it will be capable of performing full-fledged space experiments demanding high levels of skills that will be undertaken in the post-space station era and that it will render itself easily to repeated use.

3.3 Configuration of COSMO LAB

The experimental space module is comprised of an environmentally controlled pressurized module and an experimentation table exposed to space. Inside the pressurized module, preparations for experiments, their execution, analyses of the experiment results and supply services will be conducted autonomously by unmanned space experiment robots. The remote control of experiments from

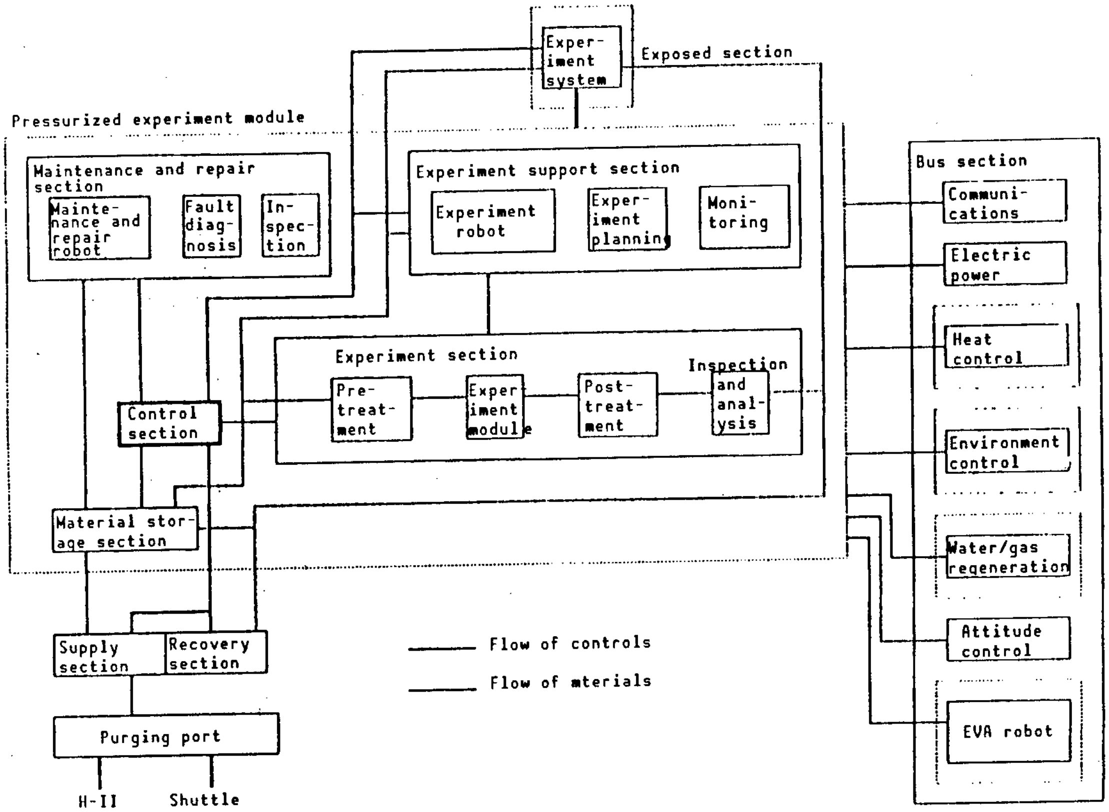

Figure 1. Block Diagram of COSMO LAB Functions

the ground by telecommunications will also become possible. Figure 1 gives a schematic diagram of COSMO LAB's configuration.

The experiment equipment will feature highly flexible construction in order to be able to meet various experimental demands. A combination of pretreatment systems, experiment modules, posttreatment systems, and analysis and measuring instruments, the experiment equipment will be configured on the image of a machine shop or FMS (flexible manufacturing system) capable of executing the required experiments.

The experiment system will be automated as much as possible. This task will be accomplished partly by the automation of the experiment modules and instruments and partly by taking advantage of the functional elements inherent in an unmanned space experiment robot. The concept underlying automation is the realization of a flexible experiment system.

3.4 Functions of COSMO LAB Robot

The specific configuration of the unmanned space experiment robots to be installed inside the COSMO LAB needs further study, but the capabilities listed in Table 2 are currently thought to be necessary.

Table 2. Major Functions of COSMO LAB Experiment Robot

Transfer function:	Transfer of testpieces and experiment instruments
Handling function:	Manipulation of experiment instruments, and exchange of testpieces
Delicate work function:	Fine-tuning manipulation of instruments and samples
Observation function:	Monitoring, visual and tactile sensors
Judgment function:	Real-time control, autonomous movements and operation
Assembly function:	Equipment assembly, wiring and piping, exchange of parts, dismantling, cleaning, etc.
Diagnosis function:	Fault diagnosis, malfunction repair
Remote work function:	(Tele-science), teleoperation

3.5 How To Conduct Experiments in COSMO LAB

We assume that experiments in COSMO LAB will be conducted autonomously, as shown in Figure 2, while maintaining contact with the ground.

(1) Ordinary experiments will be conducted autonomously by unmanned space experiment robots according to the experiment plans prepared in advance. The procedures will be monitored from the ground as needed.

(2) Depending on the nature of the experiment and tasks, the operation will be directed by relatively macro-level commands from the ground, thus enabling scientists to participate directly in the experiment.

(3) Routine inspection and maintenance jobs in orbit will be conducted unmanned.

(4) The resource control and drafting of experiment plans will be determined on the ground, but detailed task planning will be done autonomously.

3.6 Ideas on Maintenance

Equipped with orbital fault diagnosis capabilities based on the BITE function, COSMO LAB will automatically detect and predict problems in cooperation with the control center on the ground. As a result of the diagnosis, if the problem is determined to be a fault amenable to separation technology the ORU level, or if the operation needed involves routine maintenance, replacement or assembly, such as the replacement of expendables, parts requiring routine replacement, cleaning, or assembly of the experiment equipment, the

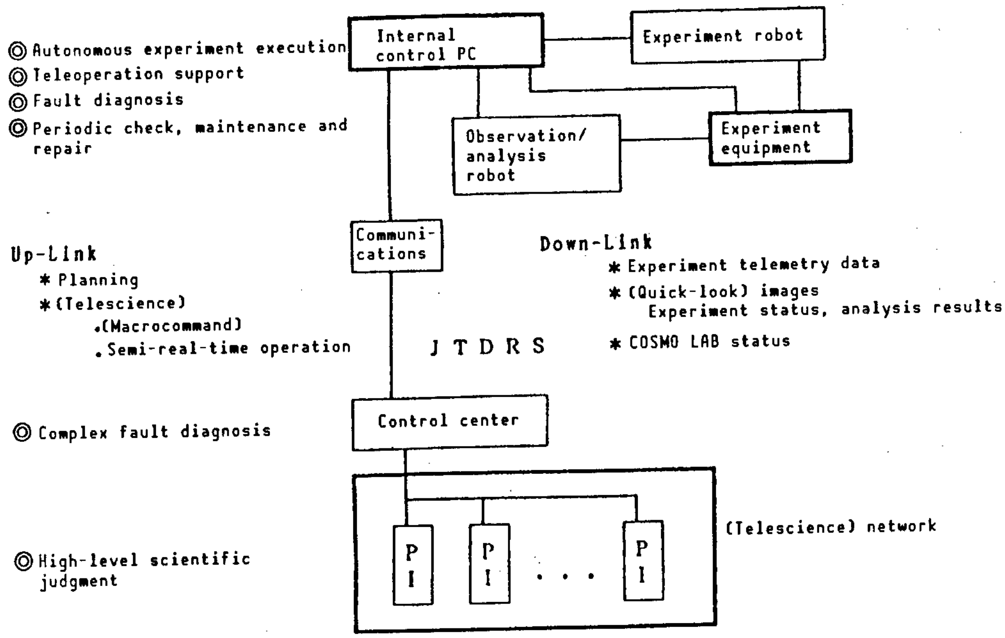

Figure 2. Experiment Operation Profile for COSMO LAB

maintenance robot will autonomously conduct the repair or restoration job according to the work procedures contained in the maintenance/repair data base. The repair operation by the maintenance robot will duly require a secondary means of support from the ground by (tele-operation).

Repair jobs that are beyond the capabilities of the maintenance robot and tele-operation, i.e., the type of problem for which countermeasures are not contained in the maintenance and repair data base, will have to be conducted by a human as a "man-tended" mode of repair activity from the space station or the ground, but studies will continue regarding this point.

3.7 Supply and Recovery Operations for COSMO LAB

The provision of experiment samples and materials to COSMO LAB and the recovery of products from the space lab will principally be conducted unmanned.

For supply or recovery, two kinds of systems will be used simultaneously. For the large-scale supply or recovery of experiment equipment or water, the supply module capable of docking unmanned, which will be lifted by the H-II rocket, will be used. For the small-scale supply of experiment testpieces, or for the "quick-return" of the experiment results, the space shuttle HOPE or recovery capsules will be used.

4. Task Analysis

As is roughly described in paragraph 2-(3), in our working group the space experiment process has been sorted and classified into the steps shown in

Table 3. Space Experiment Process

1.	Experiment planning
2.	Set-up
3.	Initial setting
4.	Preparation of samples
5.	Attachment/exchange of samples
6.	Execution of an experiment
7.	Extraction of samples, and preparation for their processing
8.	Analysis of experiment results
9.	Clearance work
10.	Maintenance and inspection
11.	Supply and recovery
12.	Storage of samples

Table 3, based on the data sheets for the FMPT and space station. The following is an outline of each of the steps.

(1) Experiment planning: In this stage, experiment plans, including release control, will be prepared, and detailed procedures for processes/tasks necessary for executing the experiment plans will be mapped out.

(2) Set-up: The required experiment equipment will be removed from the materials storage section for installation in the required positions. Resources piping systems, such as signal and power systems, will be connected, and initial adjustments and/or check-ups will be made.

(3) Initial setting: Routine inspections will be conducted, and parameters will be established based on the experiment plans.

(4) Preparation of samples: Testpieces will be selected from the storage section and, if necessary, will be measured and adjusted. The necessary treatment will be rendered so that data will be available from their testing or analysis.

(5) Attachment/exchange of samples: Testpieces will be attached to the experiment equipment or replaced with new ones, and positional adjustments will be made.

(6) Experiment execution: Specific tasks are largely influenced by the contents of the experiment and/or the experiment equipment, but they can be broadly classified into the following three: 1) observation; 2) judgment based on the observation results; and 3) manipulation based on the judgment.

(7) Extraction of samples, preparation for their processing: Samples will be removed from the equipment and fixed to the recovery vessel following a prepreservation treatment, or they will be moved to the inspection system and attached to the equipment.

(8) Result analysis: After going through the necessary processing, such as chemical treatment, the samples will be analyzed and the data obtained will be transmitted to the ground, or the data will be subjected to processing prior to preservation.

(9) Clearance work: Samples that have undergone analysis or processing prior to their preservation will be transferred for containment in a recovery or disposal vessel. The equipment will be purged of debris, and the flow pathways and experiment section will be cleaned. Then, the equipment will be examined for possible damage. Experiment systems that are not needed for the next experiment will be removed, transferred to the equipment storage section and fixed in position.

(10) Maintenance and inspection: Depending on the results of the routine inspection, fault diagnosis or diagnosis, repairs will be undertaken. The equipment's functional recovery will be confirmed, and the control and storage of replacement parts will also be undertaken.

(11) Supply and recovery: Materials and/or testpieces will be transferred between the supply module or air lock and the experiment module. The fixation and/or attachment of these materials will also be conducted.

(12) Storage of samples: Testpieces (materials, cells, plants, small animals) will be kept in good condition.

The items described in (1) through (12) are further subdivided into smaller task levels, but at these levels the shape a specific task will take will differ greatly depending on the target experiment or mission. We consider it necessary that, after detailed studies of the various requirements anticipated for the various scenarios are conducted, originality be incorporated into the space experiment process so that it will remain a flexible and general-purpose system.

5. Technical Tasks With COSMO LAB

If the COSMO LAB with features described above is to be realized, space technology based on Japan's technological accumulation in the fields of industrial robots and electronics, such as automation, robotics and computer technologies, will have to be established.

When a space experiment is to be conducted entirely in an unmanned robot environment, the tasks needing solutions can be broadly classified into:
1) tasks that are technically difficult to develop, and 2) tasks that are difficult to integrate into a system as a whole.

Detailed studies of the technical tasks associated with the development of COSMO LAB will be conducted in later study sessions, but the following are brief descriptions of the former category of major tasks that have so far been determined to pose great technical challenges in this study.

5.1 Manipulation of Small Animals

Plants and small animals will be used in the life sciences series of experiments. How to retain, grasp and manipulate these biological samples of an undefined form has yet to be established, even as a ground technique, and thus mastering the technology will pose a large technical challenge.

In the case of plants, the use of culture vessels--if the experiment permits the use of such vessels--would greatly simplify the retaining and holding operations. However, problems with the robotization of such operations as the measurement of growth and the collection of products and testpieces remain.

In experiments using small animals, the collection of body fluids and the measurement of the body conditions are basic experimental operations. If these operations are to be conducted by a robot, it will become necessary to automate and robotize such jobs as catching small moving animals, inserting needles into them for blood collection, and attaching measuring probes. In the case of animals, especially small animals, these operations will need to be conducted without damaging the test samples, so their robotization will be quite difficult.

5.2 Cleaning

Since the experiment systems aboard COSMO LAB are designed to perform a variety of experiments efficiently, they will feature flexible construction as is the case with FMS. Therefore, the experiment, analysis and disposal systems must be cleaned in orbit and the debris removed.

In experiments involving animal systems, excreta floating in the air must be removed every day to keep the breeding environment clean.

If a robot is to perform these operations, it must be equipped with the capability of recognizing the external environment.

5.3 Maintenance and Repair

COSMO LAB, as a system, is much more functional than the conventional satellite systems, and is equivalent to the space station in terms of scale. Aboard COSMO LAB, experiments will be carried out using various combinations of on-board systems, and in these experiment systems new parts or systems must be replaced routinely in order to handle the various experiments. For such systems to remain trouble-free for years without routine maintenance is believed to be an impossibility, and some inspection, maintenance and repair capabilities will be required in orbit. Aboard the space station these capabilities are to be provided by humans, but in the case of COSMO LAB these operations will be performed by robots. The following three modes of repair and maintenance by robots are being considered.

(1) A robot will autonomously perform maintenance and repair operations according to the established procedures by drawing on the maintenance and repair data base, prepared in advanced based on fault diagnosis.

(2) The expert on the ground will, through remote control, direct the orbital maintenance and repair robot by using the data and image transmitted by telemetry.

(3) A robot equipped with a high level of inductive inference and learning capabilities that will enable it to engage in the troubleshooting of problems not contained in the maintenance and repair data base will autonomously perform repair operations.

How advanced the maintenance and repair robot for use aboard COSMO LAB must be cannot be generalized because the required sophistication level is also related to its mode of operation. However, we believe that the robot must be equipped with the capability that will enable it to perform at least the routine replacement of parts or routine inspection operations 100 percent autonomously.

6. Development Plans

The development of COSMO LAB will continue by drawing on the existing space development programs so that it will be able to meet the space experiment demands at the same time that space environment utilization is in full bloom in the wake of the establishment of the space station, and it is scheduled for launching around the year 2003 (Figure 3).

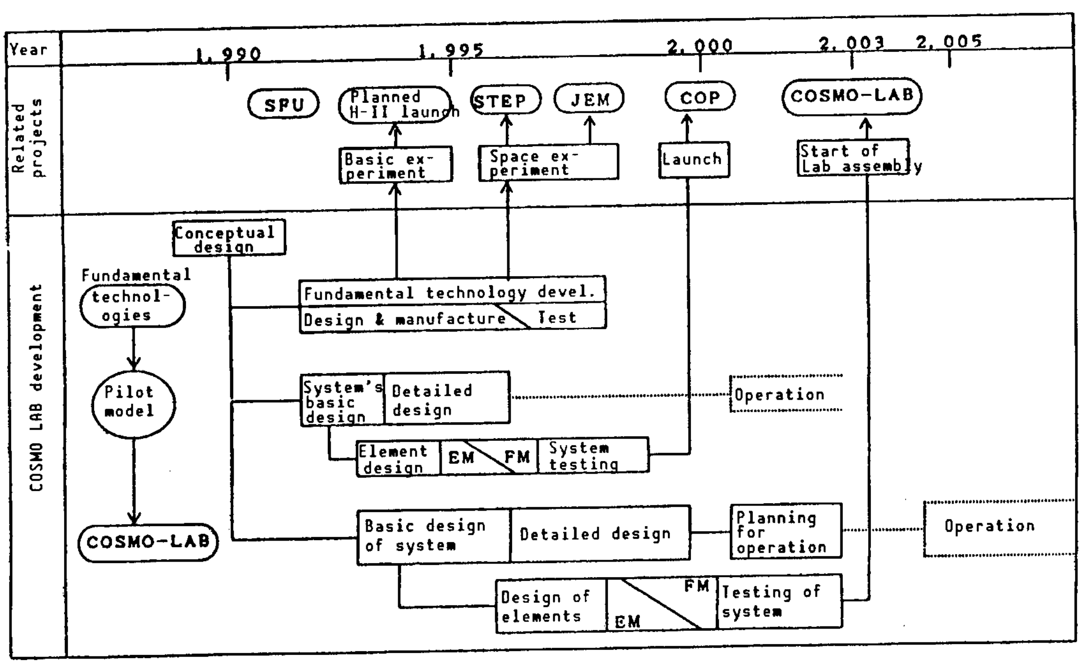

Figure 3. COSMO LAB Development Plans (Draft)

The development plans will go through the following three phases: development of fundamental technologies; demonstration of those technologies using a pilot model; and development of the COSMO LAB proper. It is believed necessary that the technologies developed during each phase of the development process be subjected to technical tests in space by taking advantage of the existing space development programs.

(1) The development of the fundamental technologies will be undertaken during the 8 year period from now until when the space station is in place. During this period, basic experiments in robotics technology will be conducted by using the H-II rocket, which is expected to become practical around 1992, and efforts will also be made for the development of fundamental technologies by using JEM and STEP.

(2) The pilot model system will incorporate the achievements of the development of fundamental technologies to realize an unmanned space experiment robot system, and experiments will be conducted to demonstrate the robot-based unmanned experiment technology. The coplanary platform, scheduled for launch around the year 2000, will be used as the bus satellite, and work for the development of the pilot model system will commence in the latter half of the 1990s.

(3) The achievements obtained during the development of the fundamental technologies and the pilot system will be incorporated into the effort toward the development of the COSMO LAB proper, and results of space experiments aboard the space station will also be fully reflected in the construction of COSMO LAB. Hence, the development of the COSMO LAB module proper will start in the latter half of the 1990s.

7. Conclusion

This paper is an interim report of the contents of studies by Working Group No 2 of the Research Forum on Space Robotics and Automation. We plan to promote studies of the robot systems required for COSMO LAB, such as the experiment robot and the maintenance and repair robot.

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